CHAPTER 9

SYSTEM QUALIFICATION

System qualification requirements and procedures for specific system qualification tests are discussed.

9-0 LIST OF SYMBOLS

A	=	rotor disk area, m^2 (ft^2)
A_{GL}	=	above ground level
A_i	=	presented area of the *i*th component or subsystem, m^2 (ft^2)
A_{Vi}	=	vulnerable area of the *i*th component or subsystem, m^2 (ft^2)
C_P	=	power coefficient, dimensionless
C_T	=	coefficient of thrust, dimensionless
E_W	=	total weapon system effectiveness, dimensionless
N_g	=	gas producer turbine speed, rpm
N_p	=	power turbine speed, rpm
N_R	=	rotor speed, rpm
P_c	=	probability of classification as to correct type of target—hard or soft, wheeled or track
$P_{C\|D}$	=	probability of classification given detection by the threat as the correct type of target
P_D	=	probability of detection of a particular target
P_E	=	probability of engagement
$P_{E\|C}$	=	probability of engagement given classification
$P_{E\|D}$	=	probability of engagement given detection
P_H	=	probability of hit
$P_{H\|E}$	=	probability of hit given engagement
P_i	=	probability of damage per hit on the *i*th component or subsystem, dimensionless
P_K	=	probability of kill
$P_{K\|H}$	=	probability of kill given a hit
P_S	=	probability of survival, dimensionless
SP_t	=	shaft power, W (hp)
V_{CRUISE}	=	cruise speed, kt
V_D	=	design dive speed, kt
V_{DL}	=	design limit airspeed, kt
V_H	=	maximum level flight speed of engine(s) intermediate power rating or power transmission system continuous rating, whichever is less, kt
V_R	=	rotation airspeed, kt
V_{STALL}	=	stall airspeed, kt
V_T	=	true airspeed for each polar flown, kt
V_X	=	best angle of climb, deg
W_t	=	test weight, N (lbf)
B	=	sideslip angle, deg
θ	=	temperature ratio, dimensionless
μ	=	advance ratio, dimensionless
ρ	=	test air density, kg/m^3 ($slug/ft^3$)
φ	=	bank angle, deg
Ω_R	=	rotor tip speed, m/s (ft/s)

9-1 INTRODUCTION

As a minimum, during system qualification of the air vehicle, the air vehicle manufacturer will demonstrate compliance with the air vehicle system specification and the Airworthiness Qualification Specification (AQS) for the air vehicle. Also system qualification is typically required for modifications to a previously approved air vehicle. Among other things, this qualification should demonstrate that functional performance, safety, survivability, component life, and effectiveness measures are according to the contractual requirements. The AQS should be a complete integrated test plan for the system or modification describing the set of minimum analysis and testing requirements that satisfy all contractual provisions. The contractual requirement for submission of additional test plans, analyses, and reports for approval by the PA should be limited to demonstration of the primary airworthiness and critical performance criteria. Elements of the AQS are described in Appendix B.

An air vehicle can be airworthy but not necessarily qualified. Early identification of operational suitability and performance deficiencies allows time for the development process. One of the major objectives of this chapter is to define the airworthiness requirements that should be verified prior to any flight testing. Safety is a driving factor behind system qualification and should be continually assessed throughout the development program. System safety assessment includes the review of component level data and review of all system operations and performance to determine the likelihood of occurrence and the severity of failures or dangerous operations. Minimum flight prerequisites should be specified by the procuring activity (PA), and the air vehicle contractor (AC) should propose methods, techniques, procedures, and conditions to be used to obtain flight approval. United States (US) Army flight approval will normally be granted in the form of a Contractor Flight Release (CFR) or Airworthiness Release (AWR), described in Appendices C and D, respectively.

A flight release indicates that the PA considers the air vehicle to be airworthy; however, issuance of a flight release by the PA does not signify qualification. A Statement of Airworthiness Qualification (SAQ) should be issued when the PA has substantiated qualification according to the AQS. A SAQ might not be issued until an Airworthiness Qualification Substantiation Report (AQSR) has been issued to document item-by-item compliance with the AQS, waivers, and deviations. Issuance of the SAQ should coincide with type classification of Standard A. Also air vehicles for the US Army are acquired in a variety of ways. The Federal Aviation Administration (FAA) or some other agency might have engineering cognizance for some air vehicles. The agency having engineering cognizance is ultimately responsible for the airworthiness qualification of that air vehicle. For instance, the FAA issues an airworthiness certificate for air vehicles conforming to an approved type design. With the increased reliance on software for flight and fire control management, the scope of possible testing combinations becomes so prohibitively large that not all combinations can be flight tested in a realistic test program. Much of this testing might be done by simulation; see Chapter 6. Whenever possible, testing requirements should be tailored to use only the most critical combinations and should be approved by the PA.

System performance is a measure of how effectively all of the subsystems work together. This phase of testing should demonstrate the synergistic effects of the characteristics of the various subsystems.

Related subsystems that individually meet contractual requirements might not satisfy air vehicle system requirements due to the accumulation of errors. An example is the weapons subsystem, in which fire control errors, round-to-round dispersion, gun pointing error, air vehicle position error, etc., might combine to make gun accuracy unsatisfactory. Flight qualification testing should demonstrate these synergistic effects in a manner which is satisfactory to the PA.

Envelope expansion and other flight airworthiness determination tests should be conducted during the system qualification phase. Based on these tests, progressively less restrictive Contractor Flight Releases and Airworthiness Releases should be issued to allow further testing of the technical performance of the system. During all flight based on these tests, progressively less restrictive Contractor Flight Releases and Airworthiness Releases should be issued to allow further testing of the technical performance of the system. and ground testing, emphasis should be on safety and reduction of risk to an acceptable level consistent with continued ground and flight operations.

Component service life information should be gathered during this phase. These initial service lives should be used to schedule component replacements, services, and inspections. As additional information is gathered during the qualification program, component lives can be calculated based on actual air vehicle loads rather than estimated loads from analysis.

Proper planning of the full system testing program should preclude duplication of flight conditions for different tests. In many cases, flight conditions used for various tests are similar, and expanded instrumentation for one test may allow full or partial accomplishment of two or more test requirements during a single set of flights. In the planning phase the AC should identify to the PA tests that can be consolidated to use test facilities, time, and resources more efficiently.

Prior to these flight and ground tests, surveys and demonstrations should be used to identify critical conditions, flight regimes, and equipment malfunctions. When approved by the PA, surveys and demonstrations should be used as much as possible to reduce test time and resources. Par. 2-4 provides a more detailed discussion of the appropriate uses of surveys and demonstrations. Formal demonstrations are used to show the capability of the air vehicle to comply with the requirements of the detail specification. These demonstrations are usually performed through a test or series of tests.

9-2 STRUCTURAL INTEGRITY DEMONSTRATIONS

This paragraph describes the general demonstration procedures necessary to prove the structural integrity of the air vehicle. Successful demonstrations should ensure that the airframe design is structurally adequate, i.e., that it meets the specified requirements for dynamic frequencies and modes, static strength, fatigue life, damage tolerance, and crashworthiness. The contractor should provide a structural integrity program plan early in the design phase to coordinate all structural-integrity-related tasks to be met and maintained over the life cycle of the air vehicle. The subparagraphs that follow describe the typical qualification test objectives and measurements of the static tests, watertightness, weight and balance, and in-flight demonstrations as part of full-scale testing.

9-2.1 STATIC TEST PROGRAM

The static test program consists of a series of tests performed on a sample airframe to confirm that loads are distributed around the frame as predicted and that the frame can withstand loads equal to those calculated for the airframe during operation. The program should verify that load paths and stresses are as predicted such that the airframe will withstand the applied loading, and identify any poor structural design details to alleviate and prevent future structural safety or maintenance difficulties. The contractor should comply with the detail requirements for static tests as stated in the contract specifications. These requirements include the support of limit loads without yielding or exhibiting deformation that would affect the safe and functional operation of the air vehicle. Requirements also include the support of ultimate loads without failure for a prescribed length of time, e.g., minimum of 3 s. Crash loads and failing loads should also be demonstrated.

A loads analysis should be used to determine the magnitude and distribution of the significant static and dynamic loads the airframe might encounter when operating within the envelope established by the structural design criteria. This analysis is based on calculated flight loads, ground loads, power plant loads, control system loads, and the effect of weapon system loads on the airframe. Environmental strength degradation should be addressed by testing at elevated temperatures with moisture-saturated specimens or properly increasing loads to account for environmental effects. Test conditions should be selected from shear, moment, and torsion diagrams that are generated for each major load condition and analytical maximum strain predictions. The conditions that produce the most shear, moment, and/or torsion for a given structure or component should be demonstrated by test. Airframe sections should be tested to ultimate or failing loads. Miscellaneous airframe structures to be individually crash load tested should also be identified, e.g., landing gear, mounts, seats, stores, and fuel cells.

The static test article should be a complete airframe and should duplicate the structure of the flight article with the following exceptions:

1. The omission of items of fixed equipment and their support structure is permissible provided it does not significantly affect the load and stress distributions and the strength or deflection of the static test article. Items in this category include furnishings, electrical and hydraulic subsystems, and avionics.

2. The use of substitute parts and/or test fixtures is permitted provided they reproduce the effects of the parts from the standpoints of strength, stiffness, mass characteristics, and load transmittal. However, the structural integrity of the parts for which substitutes are made should be demonstrated by separate tests. Several items typically in this category are rotor subsystems, power plants and accessories, and transmission subsystems.

Deliberate manufacturing flaws and/or debonds to manufacturing limits as well as subsurface delaminations might also be introduced into the test article at critical areas, if appropriate. The static test article should be fully instrumented with load cells or load transducers, axial and shear strain gages, and deflection gages. The type, number, and location of instrumentation should be sufficient to determine that load paths and stresses are as predicted.

The instrumented test article should be incrementally loaded from no load to the limit, ultimate, and failing loads in prescribed increments. In each test required, all components critical to the pertinent design conditions should be tested and loaded simultaneously. The locations of the loading fixtures should be selected to provide the best fit for the overall desired shear, moment, and torsional distributions. Hard points and other natural load points can be selected in order to preclude overloading of any local structure. Prior to failing load tests, repairs of selected critical areas may be accomplished to verify the structural adequacy of the repairs as limit and ultimate loads are achieved. The failure conditions should be applied to the static test article after the completion of all ultimate tests. To ensure the detection of structural failures, the air vehicle structure should be inspected after each test load incremental application. The applied shear and bending loads, torsional moment distributions, strain gage readings, and exterior deflections after each increment in applied loading should also be recorded to establish the rate of deflection, strain, and permanent set.

In addition to substantiating static strength, the static test vehicle also should be used to substantiate fail-safe capability. The term “fail-safe”, as applied to an air vehicle or its members, means that the structure remaining or a portion of the original structure can sustain a percentage of its design load without catastrophic failure or excessive structural deformation following the initiation of any fracture or crack. Also to be fail-safe, a part has to have a failure mode that can be monitored or that can be found by inspection prior to total failure of the air vehicle. When a fail-safe design is provided by the use of redundant attachments and/or members, a percentage of redundancy should be agreed upon by the PA. The structure should be tested to the critical fail-safe loading condition by removing members or attachments to simulate failure and increasing the load levels. Typical measurements are weight, loads, torque, stress, strain, and frequencies. Cyclic and collective positions are also measured.

2.2 WATERTIGHTNESS

Watertightness performance requirements should be clearly specified in the air vehicle specification. Watertightness qualification tests are a series of ground tests and often flight tests used to demonstrate the capability of the air vehicle to prevent water intrusion into designated watertight areas. Detailed design requirements for air vehicle watertightness should be defined in the contract specifications and approved by the PA. Information concerning testing for watertightness and water control of air vehicles in rainy weather and during air vehicle washing can be found in MIL-W-6729, *Watertightness of Aircraft, General Specifications for,* (Ref. 1).

All areas of the air vehicle should be designated as watertight or nonwatertight. Areas containing equipment that may experience adverse effects from water intrusion, including corrosion, electrical discontinuity, or any other hazard related to air vehicle safety or mission capability should be designated watertight. Considerations for designation of watertight sections should include air vehicle cleaning procedures and all environmental conditions in stowed or flight configurations, including rain, wind, humidity, driven rain, salt spray, and mist. The design and qualification demonstrations should ensure that these areas remain free from external water intrusion, migration of water from other areas, and condensation. Areas in which the presence of water will not adversely affect equipment performance should be designated nonwatertight. The design and qualification demonstrations of the air vehicle should be such that any water that enters nonwatertight sections immediately flows to the air vehicle exterior or designated drainage area.

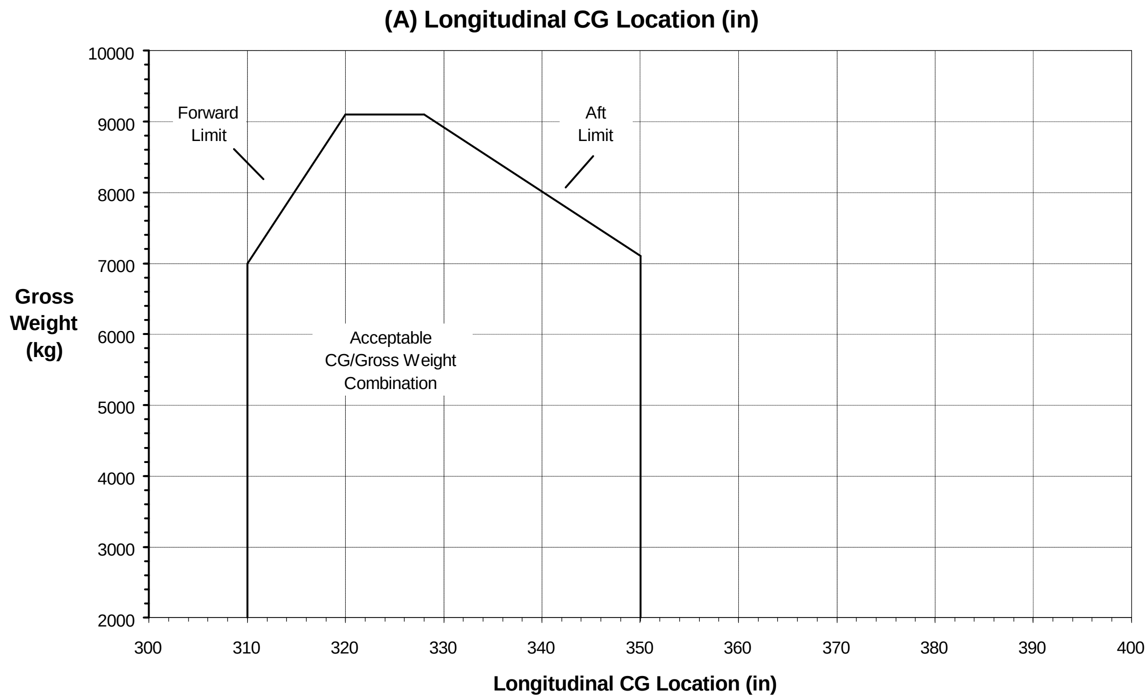
Watertightness qualification tests should be tailored to meet specific needs of the air vehicle. The test article should be complete, preflight inspected, configured for flight, and verified to be mission capable with all systems operating properly immediately prior to each specified test. As a minimum, the qualification demonstrations should include ground, ground with rainsoak, flight, and air vehicle cleaning tests. The ground and rainsoak tests should consist of a parked air vehicle subjected to a water spray system. The location, intensity, direction, and duration of the water spray should be specified in the qualification test plan. The test article should be flown in a heavy rain, as defined by the US Weather Service, for a specified time. During the flight test all compartments accessible in flight, such as cockpits and cabins, should be inspected for leaks around canopies, windshields, hatches, cockpit ventilators, and inspection or access doors. The test article should also be cleaned in accordance with the applicable cleaning procedures and checked for water intrusion during and immediately after the cleaning process.

Immediately following each qualification test the air vehicle should undergo an operational test and watertightness inspection. The air vehicle should be preflight checked, have the engines started, and be poststart checked to confirm all systems are operationally capable for flight and mission performance. Each malfunction should be assessed to determine whether it was caused by water intrusion or improper water control. Sections designated watertight should be inspected for water intrusion, water migration from other areas, and condensation. Nonwatertight sections should be inspected for any water accumulation.

9-2.3 WEIGHT AND BALANCE

Weight and balance limit determination and control are essential for safety and proper structural demonstration procedures. This allows for maximum flexibility in tactical operations and permits the rapid loading required for flight test maneuvers. Fig. 9-1 illustrates a typical center of gravity (CG) flight envelope showing a plot of weight vs CG location. The corresponding weight restrictions are shown with the lateral and longitudinal CG travel. CG limitations are usually implemented due to either controllability and handling quality issues or issues related to structural limitations. Strict adherence to weight control is required in the demonstration of test articles. The actual weights of test air vehicles and components should be verified for compliance with the design, gross, and alternate gross weights used in the structural analysis and load factor determination.

Some factors used to determine CG limits include available trim control motions, blade-flapping design limits, fatigue stresses in rotor head and blade components, and lateral and longitudinal stability requirements. Large CG offsets are balanced by small amounts of blade flapping, which increases the stresses on the blade, hub, and masts. The amount of flapping necessary to balance a large forward CG offset might become large enough to permit the blade to strike the tail boom or other fuselage structure. Other considerations include additional blade deflection occurring as a result of pilot control inputs, turbulence and/or gusts, and hard landings while testing at the maximum



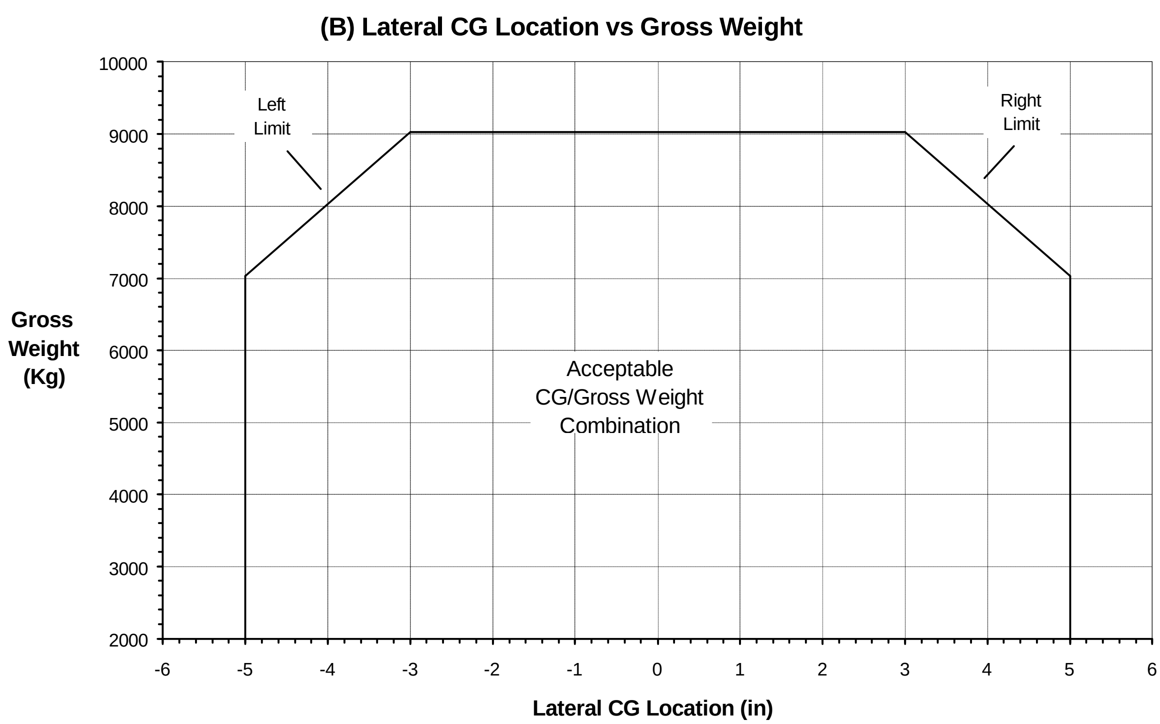


Figure 9-1 Flight CG Envelope

allowable forward CG position. The CG location also affects the longitudinal and lateral stability in forward flight. For a rotorcraft having a single-rotor, a forward CG should produce an increase in angle of attack, which produces an increase in rotor thrust and a stabilizing nose-down pitching moment about the CG. If the CG is behind the rotor shaft, the effect should be to produce a destabilizing, or nose-up, pitching moment. Alternate test configurations with external stores and equipment are destabilizing because they lower the CG and increase the instability of the rotorcraft. Rotorcraft with Tandem-rotors provide a wider range of CG without significantly affecting stability. CG limits on tandem-rotor rotorcraft are usually established for structural reasons.

Center of gravity location for aircraft with fixed wings affects not only the apparent stability but also might change the stall speed and stall characteristics and takeoff speed and takeoff characteristics. CG limits are established to ensure the pilot has control authority at the maximum limits.

Structural demonstrations are performed at the most critical weight and CG conditions. With the addition of instrumentation equipment, ballast, and representative component substitutions, it is essential that shape, mass, angular, and inertial properties are accurately resolved. The resulting load data from the structural demonstrations is used to determine safe operating and maintenance limits.

9-2.4 IN-FLIGHT LOADS

An in-flight structural test program is a substantiation of the airworthiness of the air vehicle and a formal demonstration of compliance with the structural requirements of the design specifications. The normal load factors are as specified or as limited by structural design and/or aerodynamics. The objectives of the tests are to

1. Demonstrate safe operation of the air vehicle up to the structural design envelope
2. Verify that in-flight loads used in the static and fatigue structural analysis and applied to the static test article and fatigue test specimens are not substantially different during operation of the air vehicle to the limits of the flight envelope.

The in-flight structural test typically involves flying the air vehicle in the primary mission configuration during typical flight maneuvers to record airframe and component loads data. The configuration of the test air vehicle should be identical to the proposed production air vehicle structure from the standpoint of both materials and tolerances. The addition of necessary ballast to attain specified CG locations and the installation of special test instrumentation typically are required during the tests. Demonstrations should be predominantly performed on the primary mission configuration at structural design gross weight. Additional demonstrations should also be conducted on alternate configurations, such as external stores or self-deployment at the maximum alternate gross weight. Dummy equipment having the proper shape, mass, and inertial properties may be used to simulate internally or externally mounted equipment. Any substitution or installation deviation should be approved by the PA.

The test air vehicle should have instrumentation that provides the capability to measure and record all parameters necessary to document the compliance with the demonstration requirements and to substantiate the structural integrity of the vehicle. Telemetering of critical parameters is essential because it provides instantaneous load information and thereby increases flight safety and expedites test progress. Considerations for instrumentation should include compatibility with existing Army equipment, a backup power source, redundant sources of data, crash protection, and data recovery. As a minimum, instrumentation should record control positions, control rate and sequence, performance parameters, and specific critical loads, stresses, and pressures. The complete instrumentation package should be tailored to fit the specific air vehicle within the designed weight and CG limitations.

The tests are conducted at the most critical combinations of gross weight, center of gravity, airspeed, altitude, load factor, rotor speed, and control motions. Considerations should be made for each of these parameters in the attainment of critical conditions for each test flight maneuver. The considerations should include but not be limited to

1. *Control Input*. More rapid control inputs usually generate higher loads, and the sequence of control inputs can affect loads significantly. Movement of the cyclic, collective, and directional controls (yoke and pedal for other aircraft) to the required displacements is limited in time. For example, control movement for Class I rotorcraft might be specified not to exceed 0.2 s. The controls should be held for the time required to obtain the specified load factor and should be returned in not more than the time required to the position for level, coordinated flight. Frequently, the maximum load factor is achieved by a sequence of cyclic and collective control displacement.

2. *Rotor Speed*. Rotor speed is the limit rotor speed, power on and off; the design minimum rotor speed, power on and off; and the design maximum rotor speed, power on and off. Forward airspeed and rotor speed combinations will be as limited by the transmission limit horsepower, engine power, drag, aeroelastic considerations, and any combination thereof.

3. *Weight and CG Location*. The CG positions to be used for flight maneuvers should be the maximum forward, maximum aft, maximum lateral positions, maximum vertical positions, and any CG position within this range that produces a critical loading. Most test maneuvers should be conducted at basic design gross weight, design alternate gross weight, and/or maximum gross weight.

4. *Atmospheric Conditions*. All flights should be conducted in smooth air unless specified by PA.

MIL-S-8698, *Structural Design Requirements, Helicopters,* (Ref. 2) and ADS-29, *Structural Design Criteria for Rotary Wing Aircraft,* (Ref. 3) define flight loading conditions and measurements for typical rotorcraft flight maneuvers. Title 14, Code of Federal Regulations (CFR), Part 23, *Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes,* (Ref. 4) and Title 14, CFR 25, *Airworthiness Standards: Transport Category Airplanes,* (Ref. 5) define flight loading conditions and measurements for typical aircraft maneuvers. Flight demonstrations may include symmetric pull-ups, pushovers, rolling pull-ups, dynamic yaws, sideslips, auto rotations, slope landings, hard landings, nap of the earth, and any specific combat maneuvers. Details of each test condition should be tailored to each air vehicle type and defined in the structural portion of an integrated test plan.

9-3 PROPULSION AND POWER DEMONSTRATIONS

The propulsion and power system demonstrations should be performed to demonstrate the operational and performance characteristics of the propulsion subsystem both on the ground and in flight. Demonstration of the adequacy of the entire propulsion and power system should include assurance of engine/airframe compatibility and proof of the suitability of the drive subsystem, the lubrication subsystem, the rotors, and the propellers.

Operation of a complete prototype propulsion subsystem will be the first integrated evaluation requirement. The test setup should be assembled so that all components are arranged in the proper spatial relationship. Instrumentation should be installed to measure pertinent parameters, such as pump speed (usually measured in revolutions per minute (RPM)), pressures, lubricant temperature, and flow rates. Following successful operation of the subsystem components in the bench tests, the subsystem performance should be evaluated in both ground and flight test vehicles; see Chapter 6. Additional measurements typically included during flight testing are transient rotor droop, rotor rpm, collective pitch position, pedal position, and torques.

9-3.1 ENGINE/AIRFRAME COMPATIBILITY TESTS

Compatibility of the engine and airframe should be demonstrated during steady state and transient operation. Verification of compliance should be conducted analytically prior to ground testing. The contractor should conduct safety-of-flight evaluations on the ground test air vehicle to verify basic airworthiness and show equivalence to the iron bird test; see Chapters 7 and 8. The quantifiable information that follows should be obtained for ground and flight tests:

1. Controlled rotor run-up at various advance rates and engine acceleration and deceleration capabilities during power lever manipulations
2. Engine/drivetrain torsional oscillations while operating at various altitudes, gross weights, CG locations, airspeeds, main rotor speeds, and power demand sources
3. Electrical load transfers during ground operations and as engine and generating units are brought on- or off-line
4. Starts and restarts at altitude
5. Single- and dual-engine (if any) response characteristics throughout the air vehicle envelope while applying load demands from minimum to maximum power output at various rates
6. Simulated engine failures to demonstrate access to and stability at single-engine fuel control limiters
7. Adequacy of any engine failure detection or display system
8. Acceptable power turbine governing throughout the air vehicle envelope, during both steady and transient operations, delivered from flight controls and any automatic control devices
9. Effects on engine power regulation from the fuel management system, air induction and exhaust system, local atmospheric conditions, or vibratory environment
10. Accessibility and effectiveness of all propulsion control system field adjustments.

The most significant compatibility consideration is torsional stability. The essential engine/airframe compatibility requirement is to ensure that no self-sustaining torsional oscillations will occur. Therefore, the engine should dampen any torsional oscillations above a specified frequency, whereas the rotorcraft damping system should prevent excessive rotor shaft/transmission oscillations. For torsional stability purposes the engine/airframe response at the natural frequency of the rotor subsystem is of major concern. The damping or attenuation of perturbations at this frequency should be specified as a stability requirement.

Information about determining torsional stability requirements can be found in ADS-9, Propulsion System Technical Data, (Ref. 6). The torsional stability should be analyzed showing both gain margin and phase margin throughout the operational envelope. Representative open- and closed-loop Bode plots of the power turbine-speed governor loop should be included for worst-case gain margin and worst case phase margin conditions of gas generator speed, gross weight, airspeed, outside air temperature, etc. To evaluate torsional stability, torsional system natural frequencies should be excited electronically through inputs to flight control actuators. Torsional system frequency response is then determined and analyzed to evaluate torsional stability.

9-3.1.1 Controls

Control demonstrations should be conducted on ground and flight test air vehicles. Flight tests may reveal instability not detected in the ground tests, and the engine/airframe system might be subjected to excitations at frequencies not encountered previously. Instrumentation and data collection should be conducted in the same manner for both ground and flight tests to verify stability.

Power lever control qualification includes testing of control positions, forces to move, and responsiveness. The engine power control or power turbine governor and the twist grip (if any) should be tested for loss of motion, required travel, required force, and time of any motor actuation response time. Limitations should be provided and verified for compliance by the PA. Instrumentation should include devices that indicate positions of control levers and measure the force applied to actuator linkages. Tests should be conducted for engine(s) off and engine(s) running conditions. Controls should also be included in the altitude restart demonstrations. Typical requirements for electromechanical, electronic, or electro-optic controls are defined in subpar. 9-15.4.

Engine gas generator acceleration and deceleration tests should be accomplished with and without air bleed and with automatic and manual engine power control. All tests using automatic engine power control should be run without moving the power-turbine governor beep switch to control engine output shaft speed. All power increase and decrease tests should be performed at the maximum acceleration fuel flow schedule and at the minimum deceleration fuel flow schedule. Operator methods used to increase or decrease power should be specified for each test. Data should be recorded to reveal governor transient response characteristics, torque overshoot or undershoot, transient droop or steady state droop, governor stability, and corrective actions. The tests should include power increases and decreases to specified power and torque limits. Flight tests should include test conditions conducted at incremental altitudes to a specified maximum.

Ground tests should be conducted to record the droop-compensation cam characteristics without actuation of the power-turbine speed beeper switch or control actuator. The steady state and transient droop characteristics should be obtained in flight for the range of collective pitch positions from full down to mid position and from mid position to maximum gearbox torque position. Flight tests should be conducted at two gross weights and at a preselected altitude range in specified increments. The change in rotor speed versus shaft horsepower should be verified for compliance.

Dynamic system/engine compatibility should be demonstrated at specified combinations of vehicle rotor speed and engine power settings. At each of these combinations the collective control should be cycled manually at the critical oscillation frequencies of the dynamic system and two frequencies within 0.1 Hz of critical on each side of critical. The response time of the test instrumentation for these tests should be specified, and data should be plotted as a time history.

Fig. 9-2 shows three examples of typical engine transient torque responses to a step demand for torque change. In the three examples, the torque rises to the demanded level in a relatively short time and then oscillates about that level at the natural frequency of the rotor system. One example shows a perturbation time history with a damping ratio of 0.11. This damping ratio is considered a design goal for engine response because the amplitude of the oscillation decays by more than half during the first cycle. The other two examples show a damping ratio of 0.064 and an undamped oscillation. Both of these examples illustrate unacceptable conditions. Fig. 9-3 shows the engine response time history and resulting data reduction of the transient engine torque and engine speed data. The damping ratio, frequency, and natural frequency are determined from the time history recordings as shown in Fig. 9-3.

9-3.1.2 Vibration

Vibration demonstrations should be conducted to determine the engine/airframe vibration environment in the rotorcraft. Information concerning this topic may be found in ADS-27, *Requirements for Rotorcraft Vibration Specifications, Modeling and Testing,* (Ref. 7). Modeling, ground tests, and flight tests are typically required to substantiate compliance with the vibration-related specifications.

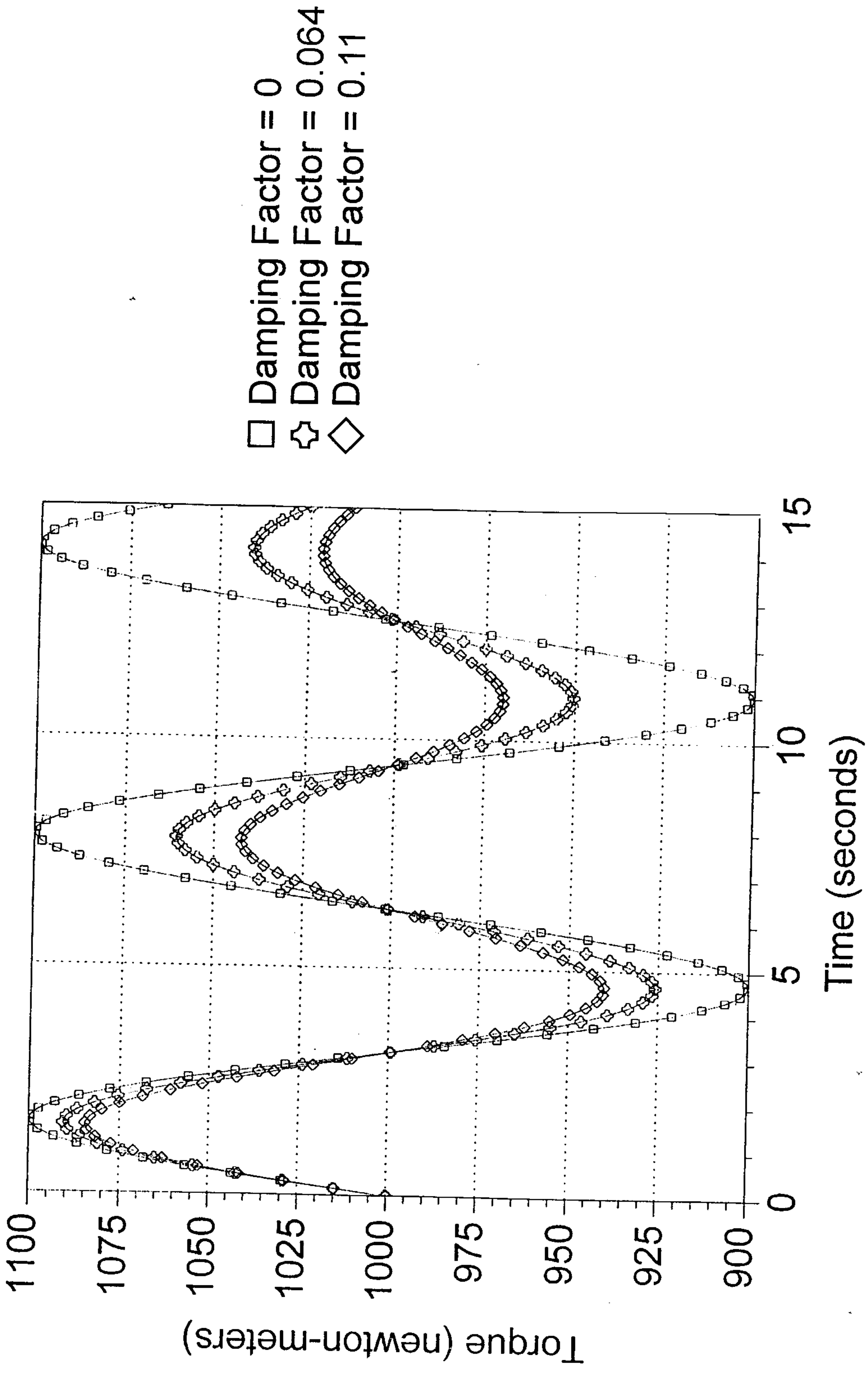
Initially, the engine manufacturer will derive modeling based on structural dynamic analysis and tests sufficient to calculate the engine bending frequencies with the engine installed on the airframe. The analytical engine compatibility modeling should be conducted with

1. The engine on the mounts and attached to a rigid structure
2. The engine on the mounts and attached to a compliant structure represented by a spring in each direction for which loads are reacted
3. The engine installation integrated with the rotorcraft dynamic model and the engine rigid body and flexible body modes defined.

A full-scale airframe shake test should also be conducted to

1. Determine the natural frequencies and other modal properties of the airframe and rotor support subsystem
2. Determine the major forced response mode shapes of the rotorcraft
3. Determine the transfer functions from force inputs at the rotor hub to the response at locations critical for vibration
4. Evaluate the effectiveness of any fixed system vibration control devices.

The engine manufacturer should define acceptable installation vibration limits by amplitude and applicable frequency for each sensor location. These vibration limits should reflect considerations of frequency of occurrence of vibration magnitudes that are representative of both steady state and transient flight conditions within a typical air vehicle mission. The test cell vibration



Source Adapted From AMCP 706-203

Figure 9-2 Transient Torque Response

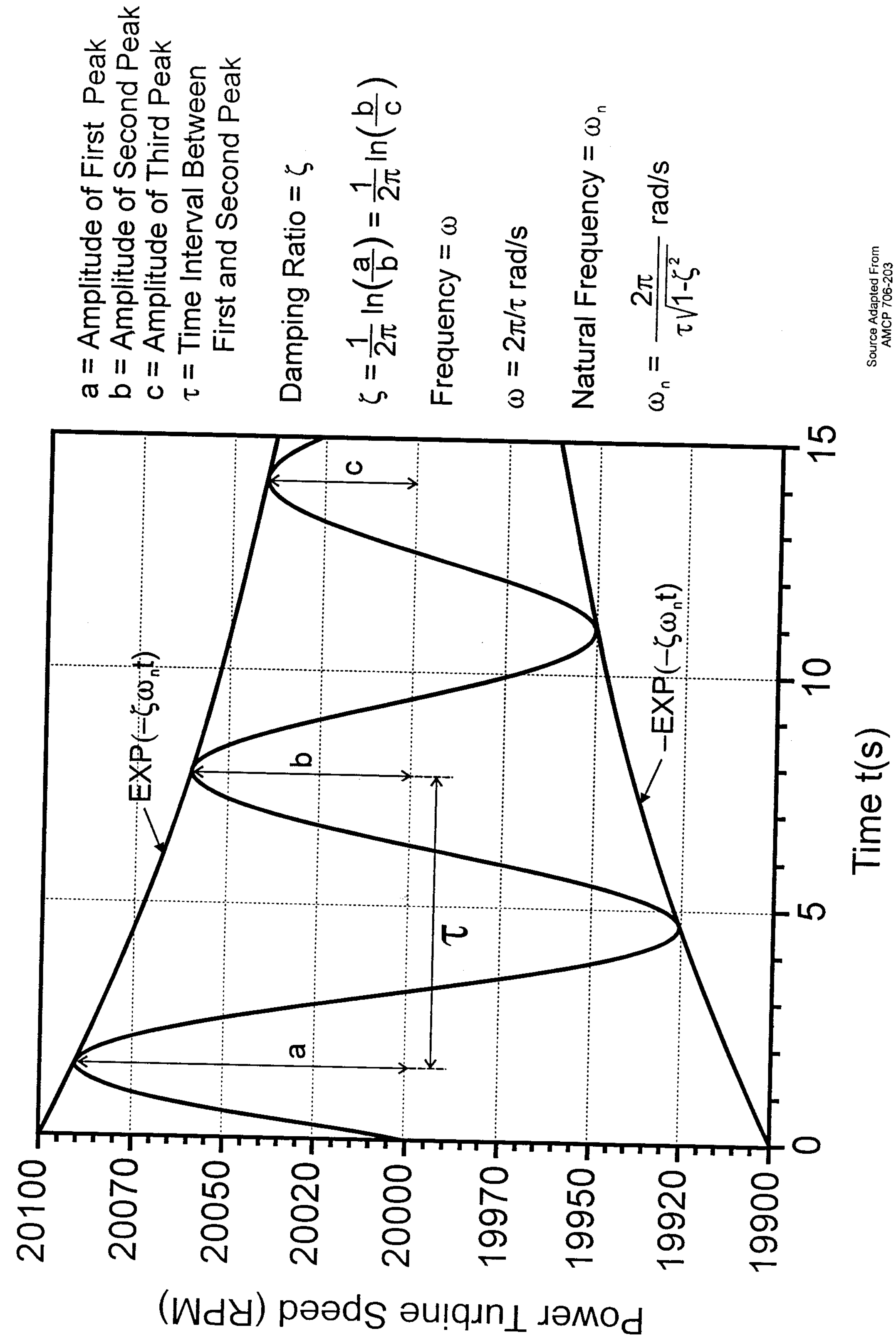


Figure 9-3 Damping Ratio and Frequency Analysis

limits for engine acceptance should be identified and compared with the installation vibration limits over the applicable frequency range. Instrumentation should include the necessary sensors and data acquisition system.

Ground tests should be conducted to record data for the most critical engine vibration conditions. Test conditions specified in the vibration survey should be the same for these demonstrations. The ground tests should be conducted for the final configuration at mission gross weight and at midrange CG unless otherwise specified.

Flight tests of the engine installation should cover specific extremes of the flight envelope that induce the highest vibrations. These tests should include the combinations of gross weight, CG, external stores, power, and flight conditions for which the air vehicle is to be qualified. The full spectrum may be flown with typical mission loading at a gross weight and CG configuration estimated to produce the highest engine vibrations. Data should be acquired at the normal, maximum, and minimum rotor speeds. The 20% of the total flight spectrum that produces the highest vibrations should then be repeated at three other gross weights and CG extremes. The effect of any special intake or exhaust duct configurations or other kits that change the engine vibratory characteristics should also be evaluated in the regimes producing the highest vibrations.

Aircraft controls such as propeller controls, thrust reversers, spoilers, etc., should be tested during ground and flight tests. 14 CFR Part 33 (Ref. 8) includes information for other aircraft engine testing requirements. Even though the aircraft is normally certified in accordance with Part 33 and 14 CFR Part 35 (Ref. 9), the US Army might supplement these requirements.

9-3.1.3 Starting

Engine-starting tests should be conducted to demonstrate the capability of the engine and its components to start within the flight envelope of the rotorcraft and to determine the adequacy of the engine shutdown and startup procedures. The ground and flight tests should be repeated a specified number of times to assure validity.

Ground tests should demonstrate compliance with component and system specification requirements, installation compatibility, and environmental engine-starting requirements. These tests should consist of two phases:

1. Initiation of the start cycle, noting start RPM, adequate voltage at exciter/vibrator, lightoff RPM within time limit, let-go RPM within time limit, engine torque/RPM, engine oil pressure, and exhaust gas temperature. Engine start performance is generally a measure of the capability to bring the engine to a stabilized idle speed within a given time and temperature limit. Fig. 9-4 illustrates an example data presentation for engine-starting characteristics plotted over start time.

2. Determination of

a. The number of consecutive start cycles without recharging or repressurizing the starter subsystem power source.

b. The number of consecutive start cycles at not less than 10 dwell point temperatures equally spaced throughout an ambient operating envelope of –54 to 52°C (–65 to 125°F)

c. The maximum interval of time between the completion of one cycle and the beginning of the next cycle

d. The starter capabilities to motor the engine

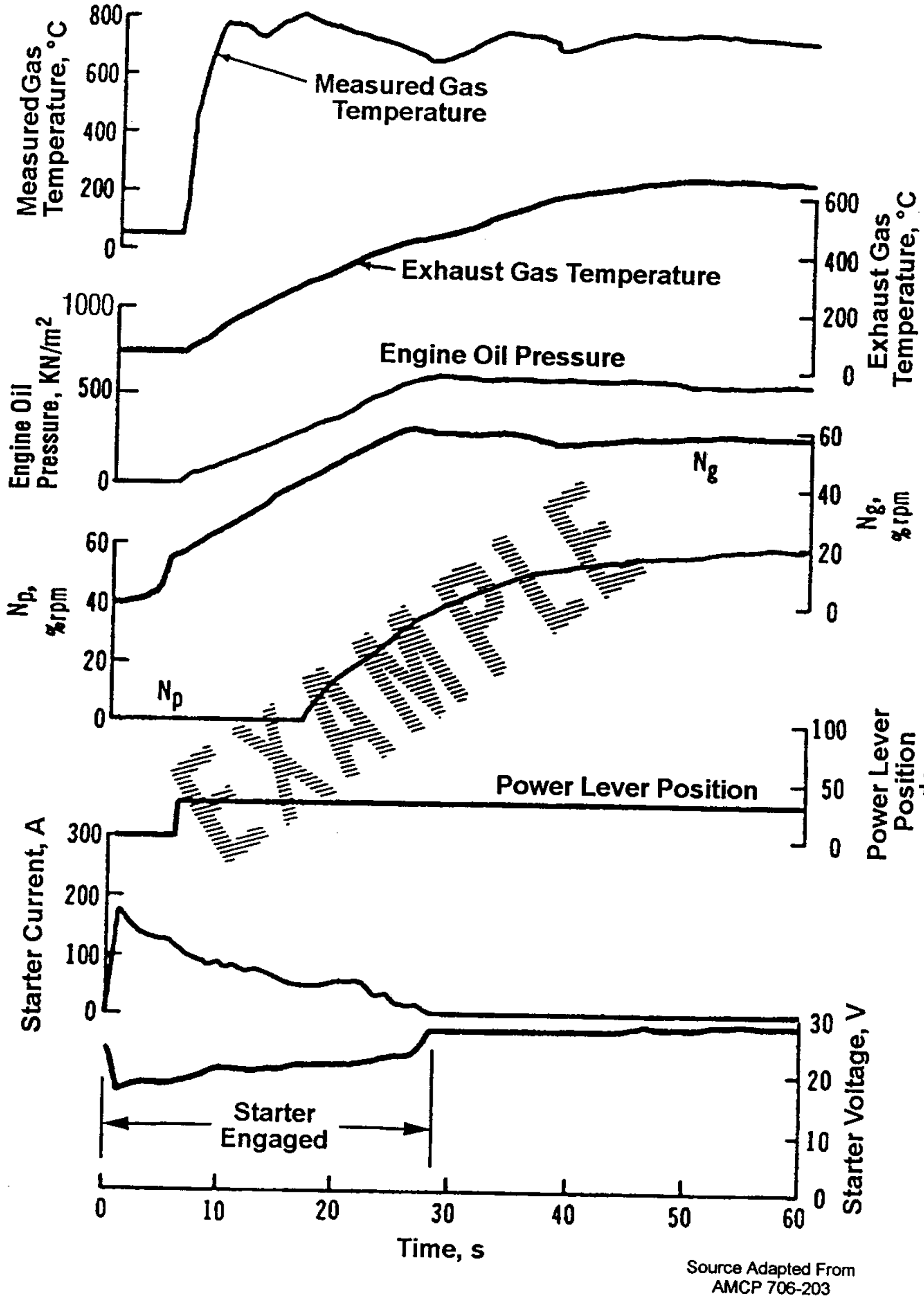


Figure 9-4 Engine-Starting Characteristics

e. The starter duty cycle for engine water wash and engine thermal stabilization. These test requirements should be performed at ambient temperature conditions as well as specified low- and/or high-temperature conditions. The engine-starting tests should also include requirements for using ground-assisted power, engine-cross-start capabilities, and any other start capabilities that are available for the system. Fig. 9-5 illustrates an example data presentation for starter performance using various power inputs and temperature conditions.

Flight tests should demonstrate altitude restarting capability, start performance variation with altitude, and the adequacy of the airborne engine shutdown and altitude restart procedures. Altitude restarts should be performed at a minimum of three altitudes from sea level to the specified service ceiling.

Instrumentation for starting tests is adequate to determine starter temperature, starter RPM, starter current or agent flow, starter terminal voltage or pressure, battery terminal voltage or pressure, time, voltage and current to exciter or vibrator, and torque output of starter.

9-3.2 PROPULSION SYSTEM TEMPERATURE TESTS

A propulsion system temperature demonstration should be conducted to determine the cooling characteristics of the air vehicle and engine-mounted components and structure under specified critical conditions. Temperature demonstrations may be conducted in conjunction with the propulsion system temperature survey, exhaust system survey, lubrication system cooling, and altitude test demonstrations. The contractor should conduct ground and flight tests to determine

1. Engine, transmission, and gearbox oil inlet and outlet temperatures

2. Temperatures of major engine components, structure, and related compartments

3. Temperatures of airframe-mounted accessories, airframe compartments, and areas affected by engine and/or auxiliary power unit and generator and/or blower exhaust impingement

4. Temperatures of the auxiliary power unit compartment and related components including associated air inlet and exhaust systems

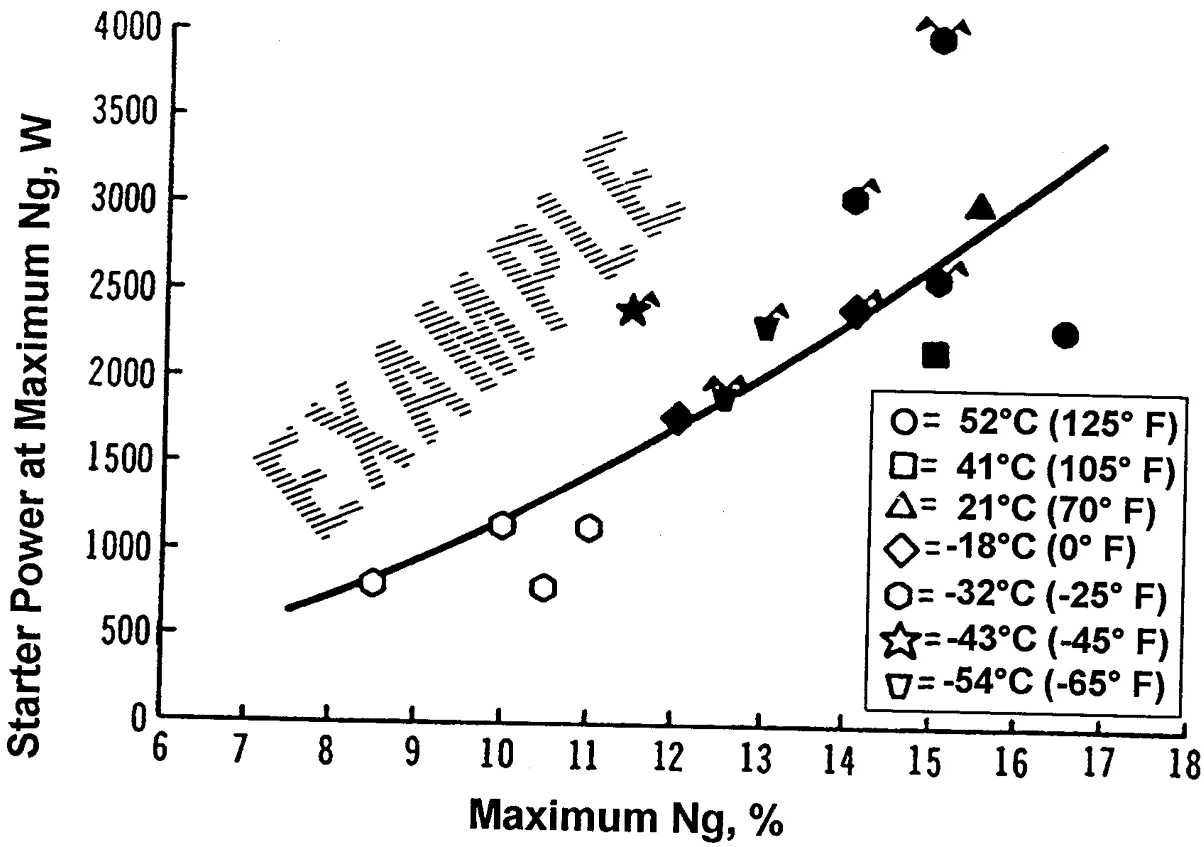
5. Heat exchanger inlet and outlet temperatures for both hot and cold fluids

6. Temperatures of infrared (IR) suppression system surfaces, structure, and related compartments.

A baseline IR-contrast signature of an unpowered (cold) air vehicle should be taken. This signature should be the reference used to determine hot-spot contributions. Measured spectral IR signature data of the unpowered air vehicle should be subtracted from the spectral signature of the powered air vehicle. The engine exhaust plume signature should be verified for compliance with the air vehicle and specification requirements.

Ground tests should be conducted at ambient conditions. The engines should be run for a specified time to allow temperatures to stabilize. Tests should be conducted under various conditions including ground idle, flight idle, 40% and 80% maximum continuous power, maximum continuous power, intermediate power, maximum power, and shutdown. Data should be recorded at established intervals through a specified time following engine shutdown.

Flight tests should be conducted at selected altitude intervals up to the service ceiling. The duration of each test should be sufficient to obtain temperature stabilization or the maximum time within design



Notes: 1. Shaded symbols indicate successful starts, open symbols indicate no start.

2. Single-flagged symbols indicate 21°C (70°F) battery used. Double-flagged symbols indicate auxilliary power unit used, and no flag indicates ambient-soaked battery used.

Source Adapted From
AMCP 706-203

Figure 9-5 Starter Performance

limitations. The level flight runs should include hover out-of-ground effect, hover in-ground effect, minimum power speed, maximum power, intermediate power, and maximum continuous power The test air vehicle should be instrumented with thermocouples and sensors placed in the required locations for adequate data collection. Pressure altitude, airspeed, engine RPM and torque, wind velocity and direction, and compartment airflow rates should be obtained in addition to the required temperature recordings. For all test conditions temperature data should be corrected to hot atmospheric conditions. Allowable operating temperature limits should be specified in the applicable air vehicle design specification or the engine/component manufacturer approved by the PA.

9-3.3 ENGINE AIR INDUCTION AND EXHAUST TESTS

The AC should conduct air induction and exhaust system demonstrations concentrating on the critical flight conditions and configurations identified during the engine air induction and exhaust system surveys. Test conditions include multiple combinations of gross weight, flight speed, flight path, altitude, temperature, power ratings, and intake and exhaust configurations. The AC should demonstrate induction and exhaust system losses and verify compliance with air vehicle and engine specifications.

The propulsion system air induction demonstration is conducted to demonstrate engine inlet pressure and temperature conditions and relate them to free-stream conditions. Engine inlet integration tests determine the compatibility and baseline engine performance influences of the air vehicle engine inlet including temperature and pressure distortion. The AC should conduct ground and flight tests to measure inlet and free-stream air temperatures and total and static pressures from which mean pressure and temperature variations across the engine inlet face can be determined. Inlet test regimes should include

1. Operation with engine anti-ice and/or deice subsystems on and off

2. Operation with the engine air induction subsystem in the normal, icing, or foreign object damage (FOD) bypass, and emergency bypass airflow modes

3. Operation in sideward and rearward flight

4. Operation in flight with varying sideslips

5. Operational characteristics of the inlet particle separator (IPS) and oil cooler subsystems with respect to engine inlet airflow and distribution

6. Demonstration of compliance with specified engine performance degradation from environmental ingestions.

The test engine will be subjected to specified bird, FOD, ice, sand, armament gas, and atmospheric water ingestions. Protection effectiveness of the inlet system against environmental ingestions should be specified by the PA.

Required instrumentation includes an instrumented inlet assembly on all engines to measure total pressure, static pressure, and total inlet temperature used to calculate inlet distortion.

The AC should demonstrate engine exhaust system characteristics during ground and flight tests to verify acceptable design practices and adequate safety of flight margins. The tests should determine the exhaust ejector effect on engine performance. The tests should also verify the IR signature suppression capability. Testing should demonstrate that the engine exhaust system meets or exceeds the hot metal and plume IR signature requirements.

The exhaust system test regimes should include

1. The effect of engine and auxiliary power unit (APU) exhaust flow characteristics on engine and APU performance
2. The effect on the exhaust characteristics resulting from convergence of various exhaust systems
3. The effect of suppressor exhaust impingement on aircraft or ground surfaces
4. The effect of exhaust flow characteristics on the performance of the IPS and engine and gearbox oil coolers.

9-3.4 HIGH-ALTITUDE CONDITIONS

Demonstrations of propulsion system performance affected by high-altitude conditions are conducted in conjunction with other qualification tests when appropriate. The engine should be subjected to altitude tests that consist of operation and air starting performance checks at selected conditions throughout the operating envelope specified in the engine specification. The test conditions should include the effects of power extraction, inlet recovery, bleed air extraction, and inlet distortion on engine performance and stability.

The control system and engine configuration should be calibrated prior to test initiation. The altitude tests should be accomplished using various specified oil and fuel grade combinations. Fuel temperature should be varied over a range sufficient to encompass all anticipated engine operating environments. Overall true root-mean-square (RMS) velocity measurements and acceleration spectrograms should be obtained for each velocity and acceleration sensor at the specified engine speed and power settings. The operating conditions selected will include at least the combination of the rated altitude(s) with the engine operating at the speed of maximum variation within the operating envelope.

Operation at each set of conditions will be of sufficient duration to stabilize the engine and to establish the performance and operating characteristics. Engine operation with the control system in control failure modes will be evaluated, and the effects on engine performance will be determined. The failure modes to be evaluated will be specified by the PA. Operation will be conducted to obtain the following data:

1. A sufficient number of altitude rating points will be selected for each altitude test condition in order to establish operating and performance characteristics. The effects of bleed air and power extraction for auxiliary engine-driven components on steady state performance will be determined at each specified test condition. The time elapsed versus engine speed, measured temperature, and fuel flow will be obtained for stability verification with the power setting at idle, maximum continuous, intermediate, and maximum.
2. The specified transient performance should be demonstrated at each rating condition. The effects of maximum bleed air and power extraction combinations on transient performance should also be determined.
3. Engine steady state and transient characteristics should be demonstrated at each test condition over the range of power settings with and without customer bleed air and power extraction.
4. Inlet airflow distortion limits and effect on transient operation and steady state performance should be demonstrated.
5. Engine in-flight starts and restarts
6. Altitude windmilling tests should be demonstrated.

Verification that the lubricating system should provide proper lubrication and operate without excessive loss of oil during windmilling operation should also be demonstrated.

9-3.5 LUBRICATION

The lubrication system demonstrations verify that the lubrication systems of the engines, transmission, and related gearboxes operate satisfactorily during critical ground and flight operations. The AC should demonstrate the adequacy of the lubrication system throughout the air vehicle flight envelope, including all attitudes within the operational flight envelope and maximum slope angles. Both steady state and transient attitudes should be demonstrated. Steady state demonstrations are limited to those attitudes sustainable by the air vehicle such as level flight, climb, and hover. Transient lubrication system demonstrations, which include quick turns, jump takeoffs, and high angle-of-bank decelerating turns, should be conducted at all attitudes up to the maneuvering limits of the air vehicle.

The test article should be an actual lubrication system as installed on the air vehicle. As a minimum, the following system-level information should be obtained:

1. Pressure measurements to evaluate line and component pressure drops and the effect on the subsystem operating characteristics
2. Dry lubrication pump priming characteristics and scavenge pump capability under all modes of operation
3. System lubricant quantity requirements and development of servicing instructions
4. Temperature measurements to establish the heat dissipation characteristics of the heat exchanger
5. Requirements of any onboard detection and diagnostic system and related sub components.
6. Chip detectors and fuzz burn-off sensors should be tested for specification compliance. The fuzz burn-off sensors should demonstrate the capability to include proper material detection and burn-off without indicating false alarms.
7. Satisfactory performance of the lubrication system after specified qualification and endurance tests.

Subsystem demonstrations should also be conducted to determine

1. Engine lubrication system quantity requirements
2. Quantity of usable oil
3. Oil reservoir expansion space
4. Oil reservoir servicing provisions
5. Oil reservoir level indication calibration
6. Oil reservoir pressure test
7. Low oil level warning operation
8. Oil vent system operation
9. Oil system bypass demonstration
10. Oil cooling demonstration.

9-3.6 FIRE DETECTION AND SUPPRESSION TESTS

The AC should functionally demonstrate, by using simulated fire sources, the installed fire detection system on the engines, APU, and in any internal weapons bay areas, when appropriate. The AC should demonstrate the adequacy of the fire-extinguishing system to meet system specification requirements as well as Federal Aviation Administration extinguishing agent requirements according to 14, Code of Federal Regulations (CFR), Part 29, *Airworthiness Standards: Transport Category Rotorcraft,* (Ref. 10); 14 CFR, Part 121, *Certification and Operations: Domestic, Flag, and Supplemental Air Carriers and Commercial Operators of Large Aircraft,* (Ref. 11); 14 CFR, Part 127, *Certification and Operations of Scheduled Air Carriers With Helicopters,* (Ref. 12);

and 14 CFR, Part 135, *Air Taxi Operators and Commercial Operators,* (Ref. 13). Tests should evaluate both main and reserve fire-extinguishing systems. All demonstrations should be consistent with the standards of the US Environmental Protection Agency.

MIL-F-7872, *Fire and Overheat Warning Systems, Continuous, Aircraft: Test and Installation of,* (Ref. 14) provides relevant information about determining performance, testing, and installation requirements of continuous-type fire and overheat warning systems for use in air vehicles. These systems are designed to use continuous lengths of heat-sensing elements connected to a monitoring device. These types of fire detection devices are usually installed in engine compartments and should be designed to withstand the normally high operating temperature of the environment without false alarms yet be sensitive enough to detect a fire quickly enough for a suppression system to be effective. MIL-F-23447, *Fire Warning Systems, Aircraft, Radiation Sensing Type; Test and Installation of*, (Ref. 15) provides relevant information about determining performance, testing, and installation requirements of radiation-sensing (surveillance-type) fire warning systems for use in air vehicle. Radiation-sensing fire detection devices are designed to produce an alarm signal when exposed to radiant energy (nonthermal) emitted by a flame. As designed and installed the system should prevent the occurrence of false fire warnings resulting from flight operations, environmental conditions, damage to components of the system, or loose connections. These fire detection systems should be demonstrated in specified environmental conditions and should record the corresponding response times. Flight demonstrations include verification that the system should not produce false alarms under various flight operating conditions. The actual ambient temperatures of the monitored spaces are also recorded during flight tests.

MIL-E-52031, *Extinguisher, Fire, Vaporizing Liquid: CF3BR; 2 3/4 Pound, With Bracket,* (Ref. 16) describes a one-time-usage, nonrefillable, handheld fire extinguisher and replacement cylinders containing 2 3/4 lb of monobromotrifluoromethane (CF3BR). These CF3BR extinguishers are being replaced by 2 1/2 lb CO2 portable bottles. Since the CF3BR extinguisher is such a common item, it might not be necessary to demonstrate discharge rates, etc. Evidence of previous qualification and demonstration typically will be acceptable. MIL-E-22285, *Extinguishing System, Fire, Aircraft, High-Rate-Discharge-Type, Installation and Test of*, (Ref. 17) describes the installation of high-rate-discharge-type fixed fire-extinguishing systems for engine spaces and other potential fire zones in air vehicles. These CF3BR extinguishers should eventually be replaced by HFC-125-CF3HF2 pentafluoroethane extinguishers. The fire-extinguishing systems are inspected for compliance with the system specifications. A pressure test of the system should be conducted to check the integrity of the tubing and fittings. The system should also be discharged under specified conditions; the duration of discharge should be timed to verify compliance.

Electroexplosive devices (EEDs), which are part of the fire suppression system, should be subjected to 20-dB safety margin testing; see subpar. 9-11.1.

9-3.7 TIE-DOWN TESTING

The total propulsion system including the engine and drive system, rotors, controls, antitorque system, APU, driven accessories, exhaust system, air induction system, and fuel systems should be subjected to demonstrations using either a test bed or the complete tied down rotorcraft. The amount of tie-down testing required is dependent on the testing completed on the ground test vehicle. The objective of the tie-down tests is to demonstrate the operational and performance characteristics of these systems and their associated interfaces. Tie-down testing demonstrates both hardware and software (if any). Also it verifies proper integration and operation of the systems prior to initial flight tests. The requirement for the tests is to demonstrate the absence of catastrophic failure modes and the fail-safe features of the dynamic components. The duration and scope of each test typically are specified by the AC and approved by the PA. As with all propulsion system qualification, tie-down tests should be conducted in conjunction with other required demonstrations whenever appropriate.

The tie-down tests should include shakedown, development, and systems enhancement testing on the tie-down test vehicle. During testing, degraded modes of operation should be demonstrated. Instrumentation should be installed to capture all necessary data adequately. Tests will include but not be limited to

1. Engine/airframe compatibility tests, including fuel control/flight control interactions, engine starts, rotor run-ups, steady state power governing, engine response performance, rotor management, and engine/airframe vibration characteristics
2. Fault insertion tests to verify adequate air vehicle behavior with loss of partial or complete authority of engine controls
3. Rotor/flight control stability checks at multiple speeds and power levels
4. Temperature margin on critical air vehicle components and related subsystems
5. Exhaust and IR suppressor operation with respect to structural integrity, cooling characteristics, vibration signature, and exhaust back pressure effects on the performance of the main engines, oil coolers, etc.
6. Fuel and lubrication system tests, compartment drainage, engine washing, and fire detection systems
7. Critical air vehicle stationary and rotating component parameters monitoring
8. Endurance tests as specified by the PA.

Postflight inspections and teardown should be performed to verify procedures, limitations, and adequacy of any modifications resulting from previous tests.

9-4 FLIGHT LOAD SURVEY

A flight load survey should be accomplished to obtain data that can be used to validate design loads or stresses for each flight condition in the maneuver spectrum defined for the air vehicle. These stress levels (mean plus oscillatory stress) should be measured for each gross weight, CG, airspeed, and altitude condition in the approved maneuver spectrum and should be used to predict component fatigue lives.

A typical rotorcraft maneuver spectrum for both scout/attack and cargo/utility rotorcraft is shown in Table 9-1, which is intended only as a sample. Component and airframe stresses should be measured for each of these maneuvers at a variety of mission gross weights and rotor speeds. In the example maneuver spectrum, the composite percentages shown for each maneuver would be used along with the measured stresses for that maneuver to determine accumulated stresses for components and airframes analytically over time. The addition of those weighted

TABLE 9-1. TYPICAL ROTORCRAFT MANEUVER SPECTRUM

EXAMPLE - Actual spectrum used should reflect aircraft's unique properties, current tactics and mission profiles.

	SCOUT/ATTACK DENSITY ALTITUDE, ft				CARGO/UTILITY DENSITY ALTITUDE, ft			
	0 to 4k	4 to 8k	> 8k		0 to 4k	4 to 8k	> 8k	
	PERCENT OF TIME				PERCENT OF TIME			
MANEUVER	40%	50%	10%	COMPOSITE*	40%	50%	10%	COMPOSITE*
Loiter A/S	20.55	19.86	18.31	19.98	18.55	17.76	17.51	18.05
Level Flight 0.6 VNE	0.83	1.68	1.61	1.33	1.53	2.88	2.71	2.32
Level Flight 0.7 VNE	1.14	1.33	0.98	1.22	1.94	1.93	1.78	1.92
Cruise 0.8 VNE	9.18	4.21	1.82	5.96	10.68	6.01	4.02	7.68
Cruise 0.9 VNE	30.42	18.71	13.03	22.83	29.42	17.71	12.23	21.85
High-Speed VNE	8.24	25.07	33.11	19.14	7.24	23.07	31.11	17.54
IGE Hover	1.54	**	**	1.54	2.64	**	**	2.64
OGE Hover	1.21			1.21	0.21			0.21
Flat Pitch	2.32			2.32	2.92			2.92
Normal Start	2.29			2.29	2.59			2.59
Normal Shutdown	1.19			1.19	1.29			1.29
IGE Turns	0.11			0.11	0.26			0.26
IGE Control Reversals	0.02			0.02	0.05			0.05
IGE Sideward Flight	0.03			0.03	0.08			0.08
IGE Rearward Flight	0.01			0.01	0.03			0.03
VTO to 40 ft and Accelerate	0.18			0.18	0.16			0.16
Normal Takeoff and Accleration	0.22			0.22	0.37			0.37
Rolling Takeoff and Acceleration	0.06			0.06	0.09			0.09
Twin Engine (TE) Roll-On Landing	0.08			0.08	0.11			0.11
TE Approach and Landing	0.38			0.38	0.48			0.48
Single Engine (SE) Approach and Landing	0.01			0.01	0.01			0.01
SE Approach With TE Recovery, IGE	0.01			0.01	0.01			0.01
TE Climb	3.00			3.00	4.36			4.36
SE Climb	0.03			0.03	0.04			0.04
Accel Climb A/S to Cruise	1.62			1.62	1.62			1.62
OGE Turns	2.99			2.99	1.99			1.99
OGE Control Reversals	0.09			0.09	0.06			0.06
Cyclic Pull-Ups	0.05			0.05	0.03			0.03
Decel to Descent A/S	2.02			2.02	2.02			2.02
TE Descent	4.84			4.84	4.84			4.84
SE Descent	0.05			0.05	0.05			0.05
TE to SE Transition in Climb	0.01			0.01	0.01			0.01
TE to SE Transition in Cruise	0.01			0.01	0.01			0.01
SE to TE Transition	0.01			0.01	0.01			0.01
Sling Load Takeoff					0.02			0.02
Sling Load Landing					0.02			0.02
Min Power Approach -Power, Recovery-IGE	0.35			0.35	0.45			0.45
Pirouette	0.01			0.01	0.01			0.01
Slope Landing	0.03			0.03	0.05			0.05
Rapid Acceleration	0.25			0.25	0.20			0.20
Rapid Deceleration	0.25			0.25	0.20			0.20
Pushover	0.17			0.17	0.17			0.17
Steep Dive	0.41			0.41	0.41			0.41
Shallow Dive	0.81			0.81	0.81			0.81
Pull-Up	0.86			0.86	0.86			0.86
High "g" Turns	0.96			0.96	0.66			0.66

*Composite spectrum to be used in life determination
**Values below this line are identical for all altitudes.

SE = single engine
TE = twin engine
A/S = airspeed
VNE = velocity not to exceed
VTO = vertical takeoff
IGE = in-ground effect
OGE = out-of-ground effect

stresses for each component should be used to predict the fatigue life of each component by the methods explained in Chapter 4 of AMCP 706-201, *Helicopter Engineering, Part One*, *Preliminary Design*, (Ref. 18). The fatigue lives of these components are used to establish the minimum component life.

Planning for the flight load survey will comply with the provisions of the approved AQS and should include but not be limited to

1. Tentative flight envelope, including design limit airspeed VDL, and gross weight and CG ranges
2. Ground and flight conditions to be examined
3. Planned instrumentation for the tests, to include structural monitoring, telemetry plans, and onboard recording
4. Data analysis and reporting procedures.

Results of the flight load survey tests may indicate that maneuvers included in the maneuver spectrum are not possible for certain altitudes, gross weights, etc. The results of the flight load survey document those findings.

9-4.1 MANEUVERS

Maneuvering flight is required to obtain flight load data at air vehicle limit conditions. Maneuvers performed during the flight load survey tests should encompass all normal operating limits anticipated for the air vehicle. Such limits will include but not be limited to mechanical subsystem limits, maximum gross weight, rotor speeds, operating altitudes, CG limits, and other applicable limits such as load factor, blade stall, vibration levels, and compressibility limits.

Flight conditions should include external and internal cargo operations for cargo and utility rotorcraft and armed configurations for scout and attack rotorcraft. The example maneuver spectrum for these two types of rotorcraft is shown in Table 9-1. Specific requirements for testing in various operational modes are covered in subpars. 9-4.1.1 through 9-4.1.5.

9-4.1.1 Air-to-Ground Scout/Attack

Once the actual maneuver spectrum to be used for flight load surveys has been established by the contractor and approved by the PA, the maneuvers typical of an air-to-ground scout/attack mission should be identified by the contractor. Typical maneuvers include mask-remask, jump takeoffs, decel-to-dash, and quick stop. Criteria used to initiate and complete the maneuver and data read options covered in subpar. 9-4.3 should be established by the AC and approved by the PA prior to testing. Consideration should be given to recording these loads sequentially with an appropriate delay to allow stabilization of the rotorcraft state. Once the rotorcraft state is stabilized, the next maneuver anticipated during this particular mission would be executed and loads recorded. All maneuvers would be executed in turn until testing is completed. Weapons firing in conjunction with maneuvers is desirable.

9-4.1.2 Cargo/Utility

Cargo/utility mission maneuvers and data requirements should be identified in the same manner used for the air-to-ground scout/attack mission, initiation and completion criteria established, and maneuvers should be conducted in a sequence similar to that of subpar. 9-4.1.1. Typical maneuvers are takeoffs, climbs, turns, cruising, and landings. Usually, these maneuvers are conducted at moderate to heavy weights. Also short-field takeoffs and landings should be considered.

9-4.1.3 Nap-of-Earth (NOE) Flight

Certain maneuvers listed in the approved maneuver spectrum are common to any rotorcraft performing NOE flight. Cyclic pull-ups immediately followed by pushovers are typical maneuvers. Also quick stops are included. These maneuvers and data read options are identified by the AC, and pilot techniques and descriptions of the maneuvers are approved by the PA prior to testing. NOE maneuvers should be flown in low-wind (less than 15 kt) conditions to reduce the environmental variability influence on the data.

9-4.1.4 Air-to-Air Combat

Some maneuvers listed in the approved maneuver spectrum might be executed differently by rotorcraft performing simulated air-to-air combat flights and might require different data read options. Typical maneuvers are pedal turns, pedal reversals, slips, pull-ups, pushovers, and the jinkings maneuver. These maneuvers and data read options should be identified by the AC, and pilot techniques and descriptions of the maneuvers should be approved by the PA prior to testing.

9-4.1.5 High-Altitude Surveillance

Maneuvers listed in the approved maneuver spectrum that are typical of high-altitude surveillance missions should be identified by the AC, and pilot techniques and descriptions of the maneuvers should be approved by the PA prior to testing. Typical operations are overgross takeoffs; slow climb to altitude; extended cruise; heavy, flat turns; and landings. Gust upsets are possible during this testing. Therefore, the AC should demonstrate prior to testing that the maneuvers planned are conservative enough to preclude any possibility of catastrophic failure due to gust upset.

9-4.2 TEST TECHNIQUES AND CONDITIONS

In the case of flight or CG envelope expansion, exceeding established pilot or control limitations, adverse weather operations, or special test techniques, maneuvers and conditions not covered by an existing Contractor Flight Release (CFR) or AWR; an updated CFR or AWR should be obtained following the procedures of Appendices C and D, respectively. If required by the PA, Government test witnessing might be required for such flights, and emerging flight load survey data might be required to obtain an updated CFR or AWR.

In-ground effect (IGE) maneuvers, such as NOE accelerations and quick stops, should generally start in low-wind conditions and accelerations should begin with a rapid application of power at a constant altitude. Normal rotor speed transients are permitted as long as the rotor speed can be stabilized at the desired value as soon as practicable. Accelerations should be terminated at airspeeds near 0.8 V_H; V_H is the maximum level flight speed at engine(s) intermediate power rating or power transmission system continuous rating, whichever is less.

Decelerations should be initiated at the same airspeed (near 0.8 V_H) by using the power required for that airspeed and should begin with a rapid cyclic flare and power reduction. Again, transient rotor speeds are permitted if stabilization is possible. Airspeed will be reduced farther at a constant altitude until a hover condition is attained.

Normal turns are entered from the desired trim airspeed and power. The turn is initiated with an approved roll rate and aft application of cyclic until a normal load factor of 1.4-1.5 g is obtained. For the test vehicle a visual “g” meter is used by the pilot. Roll out of the turn is performed by reversing the process. Any gunnery or special mission turn execution is performed according to the techniques and peak load factors approved by the PA.

Pullups and pushovers should be entered from the required airspeed and power. Cyclic control should be applied at the rate necessary to obtain load factors of 1.4 to 1.5 g for pullups and low or negative g acceleration to a level approved by the PA.

Autorotation should be entered at the desired trim airspeed and power. Entry should be performed according to the procedures approved by the PA, and descent should be stabilized at minimum rate of descent airspeed. Transition from autorotation to powered flight is the reverse of this procedure.

Control reversals and landing maneuvers should be conducted using procedures outlined in the test plan and approved by the PA.

For all maneuvers performed other than level flight, recording of data should be initiated during an initial stabilized condition, continued throughout the maneuver, and discontinued after a stabilized flight condition is once again attained.

9-4.3 LOAD MEASUREMENT

Components to be instrumented with load-sensing devices, i.e., strain gages, should be identified in the test plan and approved by the PA. These components will include but not be limited to

1. Main and tail rotor blades, propellers, and prop rotors
2. Rotor and propeller hubs
3. Main rotor, directional, and flight controls.

Location of strain gages is based on analysis of the predicted maximum strain and should be approved by the PA. The data read options to be used for each measurement are provided and justified by the AC. These read options may include

1. Read the maximum oscillatory and corresponding mean load recorded in the data record regardless of its location within the record.
2. Read the maximum positive or negative mean value and corresponding oscillatory value recorded in the record.
3. Read both the mean and oscillatory value applicable to each data record.
4. Read the mean value applicable to the data record.

Other performance parameters, such as airspeed, altitude, load factor, rotor speed, engine power, vibration levels, and control positions, should be measured to allow correlation of acceleration, load, or stress data with the maneuvers or operating conditions that produced them.

Loads and stresses in all critical dynamic components occurring during the maneuvers performed should be recorded using electronic recording techniques to allow a comprehensive analysis.

9-4.4 USAGE OF RESULTS

Once reduced, the flight load survey data should be used to establish a conservative estimate of critical component service lives; conservative is defined as underestimation of allowable service life. The AC use the methods of Chapter 4 of Ref. 18 to compute these service lives. Flight loads survey results should be reported in the structural demonstration report.

9-5 DYNAMIC STABILITY

Dynamic stability is an airworthiness criteria. The AC should demonstrate freedom from dynamic instabilities of the air vehicle throughout the operational envelope, including ground, shipboard, water, and airborne operations. Also aeroelastic and mechanical stability should be demonstrated in conjunction with any flight envelope expansion. These instabilities include but are not limited to unstable, self-excited vibrations that require no periodic force to maintain the vibration level. The AC should consider ground resonance for rotorcraft with lead-lag damper systems. Also the AC should consider aeroelastic (flutter) and mechanical stability for all air vehicles. Each of these areas is discussed in the subparagraphs that follow.

9-5.1 GROUND RESONANCE

When the frequency of the lead-lag motion of the rotor blades approaches the natural frequency of the landing gear spring system and inadequate damping is present, a violent, unstable oscillation called ground resonance can occur. Accordingly, all rotorcraft with lead-lag motion of the main rotor blades will demonstrate freedom from instability if the frequency of this mode is below or near operating rotor speed. A demonstration should also be required for the tied down configuration, if applicable.

The tests used to demonstrate freedom from this instability should include the most critical (as determined by correlated analysis) combinations of operational variables of the rotating and landing gear spring damping characteristics. The other parameters that should be evaluated include but are not limited to

1. Gear oleo servicing pressure variations
2. Percent airborne
3. Tire pressure
4. Slope landings
5. Stability augmentation system (SAS) on and off.

The AC should submit, as part of his AQS and dynamic stability testing, plans for ground resonance testing. These plans should identify excitation methods, gross weights and CG conditions to be used, methods for SAS-on and SAS-off testing, and methods of varying the parameters listed here. Provisions for motion picture and/or video coverage should be identified.

A test report should be submitted to the PA. The PA will specify the various plots of rotorcraft parameters versus rotor speed, and the test report should include those plots and a matrix of responses to those variables that clearly identifies the most critical combinations of those variables. See subpar. 9-5.3 for additional information.

9-5.2 BLADE FLUTTER

The terms aeroelastic stability and flutter are synonymous. Both rotorcraft and other aircraft might experience flutter. See subpar. 9-5.3 for additional information and guidance. Also see subpar. 6-2.5.2.

9-5.3 AEROELASTIC AND MECHANICAL STABILITY

The aeroelastic and mechanical stability airworthiness and qualification test objectives at the system level are to substantiate that main and tail rotor(s), propeller(s), proprotor(s), and fixed aerodynamic subsystem(s) have, when coupled to the airframe, adequate mechanical aeroelastic stability throughout the operational envelope, including ground, shipboard, water, and airborne operations. Ground operations should include all operating scenarios, such as rotor, propeller, or proprotor turning while tied down; rotor or proprotor coast down; run on landings and taxi operations. Shipboard operations with rotor, propeller, and proprotor turning with the air vehicle tied down, etc., should all be considered.

Aeroelastic stability analyses should be performed prior to flight. Rotating system analyses should use rotor, proprotor, or propeller rotating natural frequencies (edgewise, chordwise, and torsional) determined as a function of RPM from zero to 1.25 times normal operational rotor speed (Southwell plots) and verified by test. Fixed system analyses should use aerodynamic surface(s) natural frequencies determined for all operating configurations, i.e., wing stores, deployable surfaces, etc., and verified by test. Adequate stability margins are required and should be demonstrated for all operational combinations of rotor(s) RPM, airspeed, altitude, and load factor within the flight envelope.

Mechanical stability analyses should be performed prior to ground run. Mechanical stability is defined in this handbook to include ground resonance, drivetrain or torsional stability, and whirl mode stability. The analyses should consider all operational gross weight/center of gravity combinations (including the variation of longitudinal, lateral, vertical CG), temperature variation for temperatures ranging from –48° to 52°C (–55° to +125°F), and any two simultaneous, nonsimilar failures (i.e., simultaneous failure of one oleo and one lag damper, etc.). Adequate mechanical stability margins are required and should be demonstrated for all operational combinations of rotor(s) RPM, gross weight, CG, temperature, and simultaneous dual component failure.

Aeromechanical and aeroelastic stability should be demonstrated in conjunction with any flight envelope expansion. Stability test points typically required include

1. All corners of the flight envelope
2. Operations from various surfaces compatible with the use of the air vehicle at rotor speeds up to the maximum obtainable, including partial ground contact conditions (0 to 99% airborne)
3. A flare from autorotation at the maximum obtainable rotor speed
4. Other operating conditions identified as critical to stability.

Air vehicle configurations for these demonstrations should be shown by analysis and test to be most critical. At least three failure conditions identified as critical should also be demonstrated. Demonstration air vehicles should be equipped with a system capable of automatically exciting all relevant modes and with instrumentation capable of measuring the response of those modes.

14 CFR, Part 23, *Airworthiness Standards: Normal Utility, Acrobatic, and Commuter Category Airplanes,* (Ref. 4) and 14, CFR, Part 25, *Airworthiness Standards: Transport Category Airplanes,* (Ref. 5) should be used as a guide for required aircraft aeroelastic stability testing.

9-5.4 WING AND CONTROL SURFACE

For aircraft with fixed wings and tilt rotor aircraft, flight testing instrumentation should be used to monitor control positions and aircraft responses for evidence of loss and/or reversal of aileron or elevator control, wing and wing-aileron divergence, stabilizer-elevator divergence, and dynamic aeroelastic effects in which wing and control surface structures might be coupled with the rigid body response of the aircraft. This testing monitoring is normally conducted in conjunction with other testing. Planning for those tests should include a description of the monitoring instrumentation and methods that will measure these dynamic criterial. 14 CFR, Part 23, (Ref. 4) and 14 CFR, Part 25, (Ref. 5) allow freedom from flutter, control reversal, and divergence to be demonstrated by rational analysis if the analysis shows this freedom up to 1.2 times design dive speed V_D.

9-6 AERODYNAMIC DEMONSTRATION

The AC should conduct aerodynamic demonstrations and flight tests to verify level flight performance; rotorcraft, aircraft, and/or transition flight qualities for tilt-rotor aircraft; autorotation or unpowered glide and spin and stall characteristics; and takeoff, climb, landing, and hover performance. Collectively, these tests should have sufficient breadth of testing to provide data adequate to construct or modify the flight performance envelope section in the operator's manual. Each of these activities is covered separately in subparagraphs of this paragraph. These are typical AQS measures for both airworthiness and critical performance criteria. The methods, flight conditions and air vehicle limitations are typically proposed by the AV and incrementally authorized in the Contractor Flight Release by the PA.

9-6.1 FLIGHT PERFORMANCE TESTS

A flight performance survey and demonstration should be conducted by the AC to provide preliminary substantiation of flight performance and to provide data for inclusion in operator's manuals. The data collected and analyzed by the AC are important to validate the initial configuration. AMCP 706-204, *Engineering Design Handbook, Helicopter Performance Testing,* (Ref. 19) and Air Force Technical Report (AFTR) No. 6273, *Flight Test Engineering Handbook,* (Ref. 20) should be used as guides for data reduction and presentation.

9-6.1.1 Common

Common testing refers to tests that are common to rotorcraft and other aircraft. Flight test planning should identify the meteorological criteria for testing (calm, stable air), engine power measurement and propulsion system torque instrumentation, and calibration procedures for that instrumentation before, during, and after testing.

The AC should test and document level flight, climb, and engine performance, as required by the PA. Methods used for rotorcraft and vertical takeoff and landing (VTOL) aircraft are similar. 14 CFR, Part 33, *Airworthiness Standards: Aircraft Engines,* (Ref. 8) contains widely accepted methods used for engine testing that are applicable to a variety of air vehicle engines.

9-6.1.2 Aircraft

Performance testing for aircraft should use a widely accepted method for documentation, such as AFTR 6273, *Flight Test Engineering Handbook,* (Ref. 20). The principal purpose of aircraft with fixed wing flight performance testing is to determine lift versus drag for various configurations (flap setting, etc.) and flight conditions. A method used to accomplish this is included in Ref. 20. The lift versus drag data in combination with installed propeller (if so equipped) performance and installed engine performance can be used to calculate the following aircraft flight performance power required versus speed, power-limited speed, ceiling, climb rates, fuel flow, etc. Additional testing is required to measure specifically aircraft takeoff and landing performance, distance to clear obstacle, accelerate, stop distance, and landing distance. 14 CFR, Parts 23 and 25, (Refs. 4 and 5) contain requirements for climb with all engines operative or one engine inoperative and minimum control speed that are the design goals.

9-6.1.3 Rotorcraft

A widely accepted method used for testing level flight performance for rotorcraft includes the density-altitude/constant

$N_R/\sqrt{\ \ }\ \theta$ method. N_R is defined as rotor speed in rotations per minute, and θ is defined as the temperature ratio. This method is based on the fact that rotor performance can be uniquely described in nondimensional form with thrust and power coefficients C_T C_P, and advance ratio μ when the rotor advancing tip Mach number is constant for the range of nondimensional thrust coefficients C_T at each μ. Advance ratio μ is a nondimensional number representing rotorcraft speed divided by rotor tip speed.

Rotorcraft coefficient of thrust C_T is computed by

$$C_T = \frac{W_t}{\rho A \Omega_R{}^2}, \text{ dimensionless} \quad (9\text{-}1)$$

where

W_t	=	test weight, N (lbf)
Ψ	=	test air density, kg/m^3 (slug/ft^3)
A	=	rotor disk area, m^2 (ft^2)
A_R	=	rotor tip speed, m/s (ft/s).

Rotor disk area and tip speed are fixed. By holding the relationship of test weight and air density constant (climbing as fuel is burned off), speed-power (μC_P) polars or plots can be obtained at various airspeeds for the same C_T. The testing will involve use of PA- and AC-determined values of C_T to define vehicle flight performance.

The power required for each data point is converted to the nondimensional power coefficient C_P, which in the SI is given by

$$C_P = \frac{SP_t}{\rho A \Omega_R^3}, \text{ dimensionless} \quad (9\text{-}2a)$$

and in the English system, is given by

$$C_p = \frac{550 SP_t}{\rho A \Omega_R^3}, \text{ dimensionless} \quad (9\text{-}2b)$$

where

SP_t = shaft power, W (hp).

Finally the power coefficient is plotted against the advance ratio T, which in SI is given by

$$\mu = \frac{0.51444 V_T}{\Omega_R}, \text{ dimensionless}$$
(9-3a)

and in the English system, is given by

$$\mu = \frac{1.6878 V_T}{\Omega_R}, \text{ dimensionless} \quad (9\text{-}3b)$$

where

V_T = true airspeed for each polar flown, kt.

A cross plot can then be prepared by obtaining the appropriate values of C_T and C_P at constant values of advance ratio describing level flight performance power requirements.

Airspeeds for the best rate of climb, angle of climb, maximum rate of climb, and service ceiling should be established during climb tests. The AC should propose gross weights, power settings, density altitude ranges, and airspeeds to be used in the tests. The tests should be conducted so the effects of wind gradients (crosswind, reciprocal headings on successive data collection points) are minimized.

9-6.2 FLYING QUALITIES TESTS

The stability characteristics of air vehicles should be demonstrated by flight tests conducted in accordance with the provisions of subpars. 9-6.2.1 through

9-6.2.3 and the integrated flight test plan approved by the PA. The plan should include all of the gross weight, CG, altitude, and rotor or propeller speeds used in the testing. These tests should be conducted to establish or verify flying qualities requirements

9-6.2.1 Common

Common testing refers to testing that is common between rotorcraft and other aircraft. Common testing involves determination of static longitudinal, lateral, and directional stability and dynamic stability. However, methods used for the two types of air vehicles may differ greatly if an aircraft is qualified using 14 CFR, Parts 23 and 25, (Refs. 4 and 5) as a guide. MIL-F-8785, *Flying Qualities of Piloted Airplanes*, (Ref. 21) and ADS-33, Handling Qualities Requirements for Military Rotorcraft, (Ref. 22) both include the following:

1. Operational missions
2. Loadings
3. Moments and products of inertia
4. External stores
5. Configurations
6. Functional status
7. Definitions of service flight envelope (SFE) and operational flight envelope.

9-6.2.2 Aircraft

For aircraft with fixed wings a baseline configuration of weight (normally design gross weight), CG (normally forward and aft limits), propeller speed (normally design value), and altitude (preferably near sea level) should be chosen to conduct performance testing. Initially, the required testing should be conducted at these conditions, and configuration parameters should be varied singularly to the determine individual effects of parameter changes.

Stability derivatives are used to measure the flying qualities of the aircraft and can be obtained by using partial derivatives. As each parameter is varied, the partial derivative can be plotted against that parameter and used to imply compliance throughout the flight envelope. An example would be the partial derivative of airspeed with respect to longitudinal stick position against changing CG locations for the range of loadings evaluated. If external stores will be used, their effects on stability and control should be demonstrated.

The AC should identify the stability testing conditions to be used in the integrated flight test plan. If 14 CFR, Part 23, (Ref. 4) or 14 CFR, Part 25, (Ref. 5) is cited as the source for qualification requirements, the flight test plan should follow the guidance in those publications to determine the conditions to be used to evaluate stability of aircraft. These conditions include specific airspeeds, flap positions, landing gear status, and power settings for static longitudinal stability testing. Requirements cited in 14 CFR, Parts 23 and 25, (Refs. 4 and 5) are that the stick force curve have a stable slope for a range of airspeeds.

For static lateral and directional stability, the requirements are that stability be positive for specific ranges of airspeeds for three-control aircraft. For two-control (or simplified control) aircraft different requirements are cited including abandonment of controls for two minutes without assumption of dangerous attitudes or speeds.

Dynamic stability requirements involve testing for both short-period oscillations and combined lateral-directional (“Dutch Roll”) oscillations.

9-6.2.3 Rotorcraft

Performance testing, which is peculiar to rotorcraft, includes such testing as hover performance and handling qualities, vertical takeoffs, and slope landings. ADS-33 (Ref. 22) establishes the requirements for flying and ground handling qualities testing of Army rotorcraft. Use of this publication is meant to ensure that there are no limitations on flight safety or on mission capability due to deficiencies in flying qualities. Handling qualities are specified in terms of three levels, and the synergistic effect of several Level 2 areas could result in a Level 3 total rating (the lowest).

The AC should demonstrate flying qualities for rotorcraft. Information about this topic can be found in ADS-33 (Ref. 22).

9-6.3 TRANSITION FLIGHT QUALITIES TESTS

For air vehicles that can transition from vertical takeoff and landing (VTOL) or vertical/short takeoff and landing (V/STOL) (primarily rotorcraft) modes to fixed wing modes, the AC should conduct tests and demonstrations necessary to determine flying qualities during the transition operations.

In some cases two or more possible flight configurations might be possible at the same test conditions. An example could be flight at 90 kt and maximum gross weight that might be possible with the engine nacelles/thrust vectors in the VTOL mode (0 deg inclination to the vertical plane), in the fixed wing mode (90-deg inclination), or any inclination between those values.

The integrated flight test plan should, as a minimum, identify airspeeds, altitudes, propeller/proprotor speeds, thrust inclination for normal envelopes and for emergency envelopes with one-engine inoperative (OEI) operations, and gross weights to be tested for demonstrating transition flying qualities. Handling qualities and flight performance margins should be demonstrated to establish a transition flight envelope.

The tests and demonstrations should be documented in accordance with par. 9-6. Future revisions of ADS-33 (Ref. 22) may contain specific handling quality requirements for this mode of flight. Until then, MIL-F-83300, *Flying Qualities of Piloted V/STOL Aircraft*, (Ref. 23) should be used for this purpose.

9-6.4 AUTOROTATION OR UNPOWERED GLIDE

The AC should demonstrate the autorotation, or unpowered glide, characteristics of the rotocraft in accordance with the approved test plan. During this testing, safety of operators and ground crew members should be emphasized because establishment of limited power envelopes, such as the height-velocity (HV) envelope of Fig. 9-6, are among the most dangerous tests to be attempted.

9-6.4.1 Common

Common testing refers to testing that is common to rotorcraft and other aircraft. All air vehicles tested should demonstrate their rates of descent as a function of airspeed and altitude. The effects of the rate of descent on calibrated airspeed while the air vehicle is in unpowered descent should be established, and all data presented should be in operational terms such as impact on minimum rate of descent speed and stall speeds.

9-6.4.2 Aircraft

For aircraft with fixed wings the AC should establish parameters for unpowered glide. Typical parameters may include rates of descent at various airspeeds and altitudes, propeller speed and pitch limits, and other requirements of 14 CFR, Part 23 (Ref. 4) or Part 25 (Ref. 5).

9-6.4.3 Rotorcraft

The AC should demonstrate the autorotational performance of rotorcraft and should consider, as a minimum, four areas for evaluation. These areas are steady state autorotation performance, establishment of a height-velocity envelope, performance during partial power descents, and stability during autorotation entries.

Steady state autorotation performance should be established as a function of rotor speed, airspeed, density altitude, and gross weight. The envelope exploration, such as the sawtooth descent test technique, may be specified in the Contractor Flight Release. The sawtooth test method is a series of timed climbs and descents at varying airspeeds, through a given altitude band and alternating the climbs and descents. These tests should include performance at the most critical conditions for high and low rotor speed and rates of descent. Normally, the low-altitude, low-gross-weight condition should coincide with lower rotor speeds, and the high-altitude, high-gross-weight condition should be most conducive to rotor overspeed.

The HV envelope should be established by the AC using a method that minimizes actual hazard exposure and potential damage. One such method establishes this envelope by entry into autorotation at successively lower absolute altitudes for each airspeed tested. After an agreed-upon delay in reducing collective thrust, the rotorcraft should enter an autorotational descent, adjust airspeed in accordance with the approved integrated test plan, and land. The contractor should conclude testing at an airspeed at which some limiting condition, such as minimum airspeed attainable or maximum rate of descent, is encountered, and that airspeed and altitude should constitute a data point for establishment of the HV envelope. An example of this envelope is shown at Fig. 9-6. There are two upper boundaries in Fig. 9-6—one for low gross weight and one for high gross weight. Together with the lower boundary, the upper boundaries identify airspeed and altitude conditions that should be avoided. Complete failure while operating within those boundaries would probably result in damage to the rotorcraft and/or injury to occupants despite the best efforts of the pilot. In Fig. 9-6 a low-altitude, high-speed boundary is also shown that is an avoidance region for the same reasons.

Partial power descent performance should be established for multiengine rotorcraft as it is for the HV envelopes. These envelopes should identify the gross weights at which the rotorcraft cannot hover IGE after loss of one engine and any avoidance regions. Performance curves (power required versus airspeed and gross weight) for single-engine rotorcraft may be used to estimate partial power descent performance if a reduced power condition occurs.

The AC should also demonstrate that the rotorcraft has acceptable handling qualities and safe rotor decay characteristics following a power failure. The flight envelope used for this demonstration should involve all authorized flight conditions and gross weights . Entry procedures; delay times for collective pitch; and longitudinal,

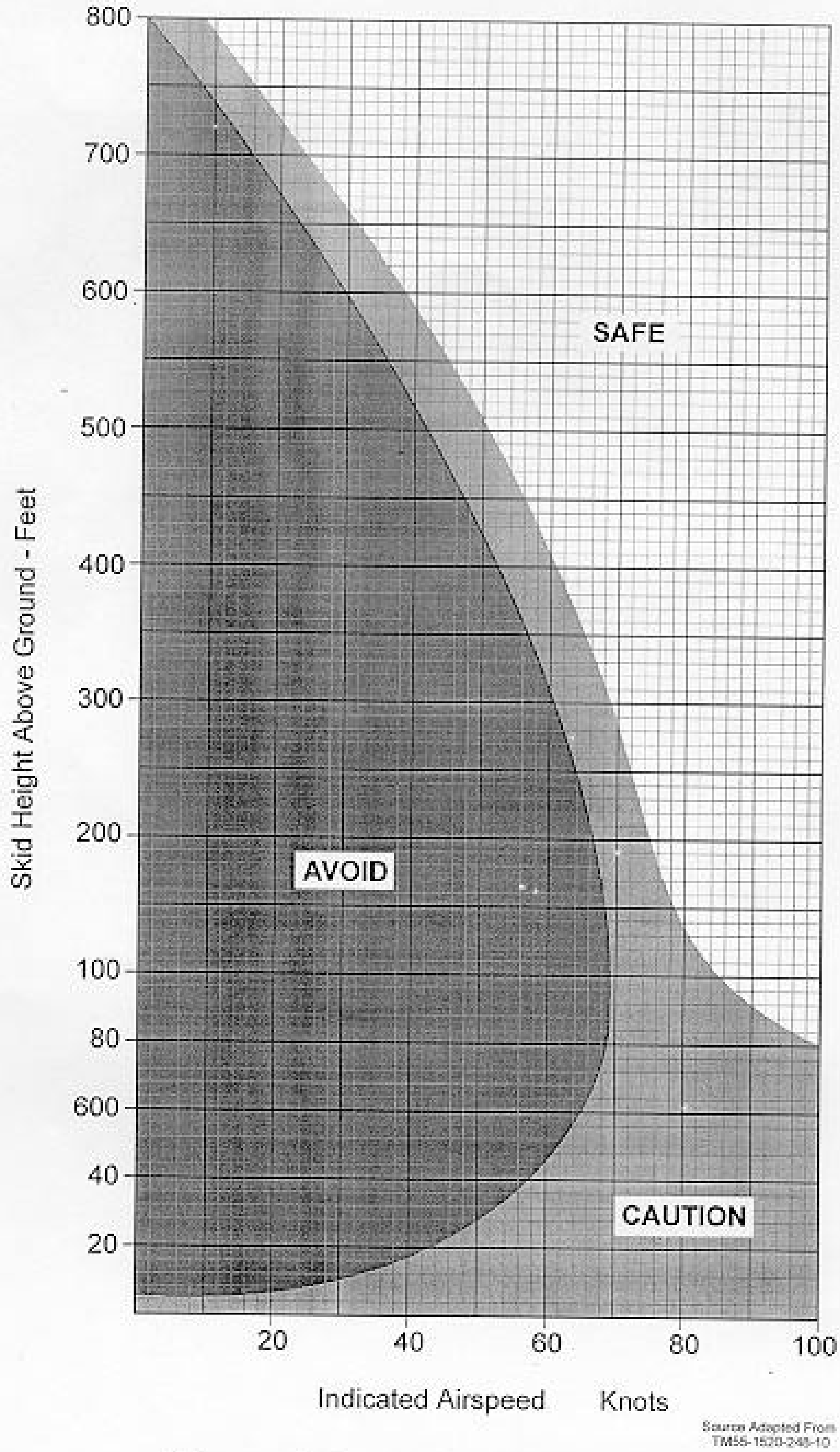


Figure 9-6. Height Velocity Diagram

lateral, and yaw control adjustment following power reduction should be in the flight test plan.

9-6.5 SPIN AND STALL CHARACTERISTICS

Spin and stall characteristics testing is conducted to determine the airworthy limit airspeeds at which the stalls and spins occur, indications to the pilot that the condition is about to occur, and the appropriate recovery response after the occurrence. If 14 CFR, Part 23, (Ref. 4) is adopted by the PA to specify spin and stall characteristics for aircraft, the AC should demonstrate that spin and stall characteristics are in accordance with the provisions of subpars. 23.201 through 23.221 of Ref. 4. Prior to initiation of testing, the AC should identify which category of criteria (normal, utility, or acrobatic) the AC intends to test against. The PA should specify exceptions to wing and cowl flap, landing gear, power, trim, and propeller criteria cited in 14 CFR, Part 23, (Ref. 4), if applicable. The PA should also specify or approve the contractor's proposed criteria for determining when an aircraft has encountered excessive loss of altitude, undue pitch-up, or uncontrollable tendency to spin.

If 14 CFR, Part 23, (Ref. 4) is not specified by the PA, the AC should develop a test plan to demonstrate recovery from stalls and spins. Demonstration of stall recovery should include recovery from the following types of stalls: wing-level stalls, turning flight stalls, accelerated stalls, and critical engine inoperative stalls. This test plan should follow the general guidelines of 14 CFR, Part 23, (Ref. 4), as applicable.

Regardless of the demonstration method, test results will be documented in accordance with par. 9-6.

9-6.6 TAKEOFF

Takeoff performance should be demonstrated with the aircraft at gross weights, altitudes, temperatures, configurations, engine power ratings, and CG locations approved by the PA. The purpose of these demonstrations is to determine takeoff distances required and obstacle clearance capabilities, to provide preliminary data for inclusion in technical manuals, and to verify specification compliance.

9-6.6.1 Common

Both aircraft and rotorcraft takeoff performance testing should demonstrate the runway or takeoff distance required to clear an obstacle of a set height (usually 15.2 m (50 ft). 14 CFR, Part 23, (Ref. 4) has set 10.7 m (35 ft) as the height for commuter category aircraft. This distance should be the horizontal distance measured from the point on or above the takeoff surface where the takeoff begins to the point along the takeoff path at which the required height above ground level (AGL) is reached.

For normal takeoffs the maneuver is similar for rotorcraft and other aircraft except for height above ground. Rotorcraft and other aircraft typically accelerate at a predetermined power setting to rotation airspeed VR,, rotate to a predetermined pitch angle, and accelerate to best angle of climb VX.. The means used to determine best angle of climb varies. Obstacle clearance capabilities should be calculated in advance for given ambient conditions. Loss of power implications should be considered. Rotorcraft-peculiar takeoff demonstrations are covered in subpar. 9-6.6.3.

Service ceilings should be determined by the AC for conditions with all engines operating and OEI for multiengined aircraft. The service ceiling is defined as the maximum pressure altitude at which a 30.5-m/min (100-ft/min) climb can be maintained for a given temperature, gross weight, and engine power setting.

Data should be collected to allow plots of rates of climb (R/C) versus torque change at various gross weights, configurations, and airspeeds approved by the PA.

9-6.6.2 Aircraft

14 CFR, Part 23,(Ref. 4) and Part 25 (Ref. 5) contain detailed requirements peculiar to aircraft takeoff and climb. These requirements should be used as a guide for demonstration of aircraft takeoff and climb characteristics. Tests should include crosswind takeoffs at the maximum allowable limits and aborted takeoff tests. Aircraft takeoff tests should also include tests to demonstrate the capability to maintain aircraft control during loss of thrust during the takeoff roll and loss of thrust after takeoff.

9-6.6.3 Rotorcraft

Rotorcraft takeoff demonstrations should include demonstrations of two other takeoff modes if required by the PA. These two modes are vertical takeoff and terrain flight takeoff.

Vertical takeoffs should be demonstrated for gross weights, altitudes, and temperatures specified by the PA. To perform this type of takeoff, the rotorcraft must have power in excess of that required to hover out of ground effect (OGE). Demonstration of required hover power is discussed in subpar. 9-6.8. Usually, these requirements are stated as a vertical rate of climb (VROC) at the specified gross weight and atmospheric conditions.

If specified by the PA, the AC should demonstrate terrain flight takeoffs. After verification that hover OGE is possible, these takeoffs begin from the normal takeoff position. However, a constant climb angle is used as the rotorcraft accelerates to specified obstacle clearance height. Once that height is reached, climb is discontinued, and the aircraft transitions to level terrain flight.

9-6.7 LANDING

The North Atlantic Treaty Organization (NATO) Advisory Group for Aeronautical Research and Development (AGARD) *Flight Test Manual, Volume 1, Performance,* (Ref. 24) defines landing as the process in which an aircraft is safely brought from a safe flight condition to a standstill. The AC should demonstrate landing performance according to the approved AQS using flight conditions and aircraft configurations approved by the PA. Information obtained during this testing should be used to establish emergency procedures for engine-out landing of multiengined aircraft.

9-6.7.1 Common

The AGARD *Flight Test Manual* stresses the steady, controlled nature of measurements such as rate of descent, angle of approach, and approach airspeed and the division of each landing test into air and ground run phases. The air phase encompasses all activities prior to touchdown, and the ground run phase begins when the aircraft touches down on the landing surface. The standard values or range of allowable values for measurements of airspeed, rate of descent, and/or angle of approach, combinations of gross weight, CG location, altitudes, and rotor or propeller speeds should be established before testing and incrementally explored .

Measurements that might vary from test to test include ground speed at obstacle height, ground speed at touchdown, air phase time, air phase distance, ground distance, wind speed, air temperature, and air pressure. When braking distance is of concern, the air vehicle should be equipped with a means to measure consistent application of braking force, such as a longitudinal accelerometer.

9-6.7.2 Aircraft

The landing airspeed chosen should be such that for aircraft airspeed is sufficiently above stall airspeed V_{STALL} to provide positive control and recovery in the event of an emergency, such as a single-engine failure on a multiengined aircraft. If 14 CFR, Part 23, (Ref. 4) or Part 25, (Ref. 5) is used as a basis for qualification, approach airspeed will be above 1.3 V_{STALL}.

Prior to testing, the standard approach technique should be established, and airspeeds and rates of descent or flight path angles typically are specified along with the data to be collected, collection methods, reduction techniques, and acceptable values for the landing parameters.

9-6.7.3 Rotorcraft

AMCP 706-204, *Helicopter Performance Testing,* (Ref. 19) contains detailed requirements for conducting rotorcraft landing performance tests. Traditional methods are covered that stress testing constant airspeeds throughout landing descent. Measurements include horizontal distance to clear a 15.2-m (50-ft) obstacle, rate of descent, and gear load at touchdown. Data reduction forms for these measurements are shown in Table 11-3 of AMCP 706-204 (Ref. 19). Any additional limitations, such as collective pitch limits or stability and control concerns, may also establish limits for minimum descent airspeed and will be documented by the AC.

For rotorcraft one constant landing airspeed may not be required. Subject to approval by the PA, an alternate method may be used in which the air phase is flown with a steady rate of descent or angle of approach with airspeed steadily decreasing to the approved value (zero for approach to hover). The information gained from use of this method can then be used to establish emergency procedures for rolling landings, such as minimum touchdown airspeed.

Vertical landing tests should be conducted to verify specification compliance. These tests should be conducted according to AMCP 706-204 (Ref. 19) and the approved AQS.

9-6.8 HOVER

Hover flight performance while a rotorcraft or VTOL aircraft is out of ground effect should be demonstrated by the AC. Also hover flight performance should be demonstrated in winds up to 45 kt from any azimuth. Critical azimuth locations (if any) should be demonstrated and documented. The demonstration plan should detail methods, test gross weights, rotor speeds, and height above ground measuring techniques. Hover performance testing should be accomplished prior to landing performance testing according to AMCP 706-204.

The method described in subpar. 9-6.1.3 is an acceptable one to use to demonstrate hover flight performance. However, the importance of calm wind conditions, significant variation in gross weight and/or rotor speeds, and density altitudes should be stressed by the PA during test planning.

Height above ground is commonly measured by one of two techniques. The first technique involves use of a weighted, measured cord and a ground observer to talk the aircrew to the exact height. The second involves hovering at an exact height with the helicopter attached to a load cell on the ground. In this method, rotor thrust is equal to the helicopter weight plus load cell reading, allowing significant variations of C_T during one test flight.

Typical test results should include plots of C_T versus C_P for lines of constant height AGL and maximum hover gross weight versus pressure altitude along lines of constant temperature.

9-7 TOTAL SYSTEM VIBRATION TESTS

Total system vibration tests include ground vibration tests and flight vibration tests. Ground vibration tests are required to confirm that the mode shapes and natural frequencies of the airframe and rotor systems are consistent with earlier analyses. Normally, these analyses result in changes to the design configuration to ensure that helicopter modal frequencies do not coincide with the normal operating range of rotor speeds.

The flight vibration tests are conducted to determine whether vibration levels at crew and personnel stations are acceptable and to investigate vibration levels occurring at selected equipment locations. The vibratory requirements of ADS-27 (Ref. 7) typically apply.

As a minimum, the vibration testing plan should address the methods, conditions, configurations, data collection and analysis techniques, excitation means, schedules, relationships to previous vibration testing, firing tests, stability testing, and acceptance criteria.

Documentation of vibration tests should be according to par. 6 of ADS-27 and the approved AQS unless otherwise specified by the PA.

9-7.1 GROUND VIBRATION TESTS

The two primary types of ground vibration tests are airframe vibration (shake) tests and rotor system vibration tests needed to determine rotor blade and hub properties.

As early as possible in the development process, a full-scale airframe shake test should be conducted to confirm mode shapes and verify that natural frequencies of the airframe and rotor systems do not coincide with rotorcraft excitation frequencies during normal operations. Other purposes of the shake test are listed in ADS-27 (Ref. 7) as are the configurations to be tested and the requirement to repeat the testing using the final production configuration. For this test the mass of the main rotor blades should be simulated in the manner that based on analysis best represents the operating condition. Other airframe items should be installed in their normal operational position or a dynamically similar model of the item should be installed. The ground vibration test should be conducted with the rotorcraft completely suspended from the rotor hub(s) to simulate flight and with the critical gross weight on the landing gear and at intermediate conditions as needed. ADS-27 contains provisions that eliminate the requirement to have the critical gross weight on the landing gear.

Accelerometers are used to record responses to applied excitations. In the test plan the AC should identify accelerometer locations adequate to measure vertical, lateral, longitudinal, and torsional accelerations. Accelerometer locations should also be identified for external stores and for wings and empennages.

Shake tests should be conducted across a frequency range approved by the Government. Normally, this range should be from just above the natural frequency of the suspended helicopter to at least 50 Hz. Accelerometers and appropriate recording devices should be used to document responses to excitations by plotting single accelerometer readings, by unfiltered recording of all signals, or by plotting all accelerometer readings at frequencies of interest, such as main rotor frequencies. If testing at frequencies above 50 Hz is required, the AC should identify the techniques and methods to be used to interpret complex responses.

If ground resonance or mechanical instability is possible (lowest main rotor in-plane natural frequency at or below normal operating rotor speed), additional vibration testing should be performed to determine the effective hub mass, hub damping, and hub natural frequency. The aircraft should rest with all of its weight (not suspended) on a surface similar to the surface from which it will operate. Alternate landing gear configurations and representative tire or pneumatic float pressures should be tested for each landing condition. The effects of temperature on hub mass, damping, and natural frequency should be evaluated by using temperature ranges cited in the detailed aircraft specification. If temperature variations affect mechanical stability, the PA may require additional testing at the more critical temperature(s).

Prior to first flight, rotor system vibration testing needed to determine rotor blade and hub properties should be conducted. These tests are detailed in par. 5.2 of ADS-27 (Ref. 7) and include rotor blade and hub properties determination, control coupling, and rotor frequency tests. Nonrotating natural frequencies, both in and out of the plane of rotation (chordwise and flapwise), should be determined for all rotor blades. If applicable, the rotor blades should be mounted in the hub, which is suspended so that the vertical natural frequency of the suspended rotor system should be less than one-half of the calculated value of the lowest natural frequency being investigated. For these tests excitation may be applied to either the hub or a point on the blade appropriate to the mode under investigation.

Plots of the computed coupled natural frequencies versus operating speed should be prepared in a similar manner to the typical plots shown in Fig. 9-7.

9-7.2 FLIGHT VIBRATION TESTS

An in-flight vibration survey of the air vehicle should be conducted by the AC. Information about defining vibration performance levels or intrusion indices at all crew and passenger stations can be found in ADS-27 (Ref. 7). Vertical, longitudinal, and lateral vibration levels should be measured with accelerometers located at stations that will realistically represent what occupants feel.

For rotorcraft, sensitivity to main and tail rotor out-of-balance and out-of-track conditions should be investigated. Vibratory surveys on new air vehicles should also include data collection on equipment outside the crew and passenger compartments. For a new air vehicle, vibration pickups will be installed along the fuselage, wings, empennage, and transmission or main rotor mounting.

ADS-27 defines four flight regions that should be tested for rotorcraft and tilt rotor aircraft vibration specification compliance. Region I consists of all steady flight conditions with load factors between 0.75 and 1.25 g and airspeeds from hover to cruise V_{CRUISE} and to the maximum rearward and sideward flight speeds while operating within the defined power-on rotor speed limits. Region II applies to all flight conditions outside Region I with durations greater than 3 s, Region III applies to Region II flight conditions with durations less than 3 s, and Region IV applies only to tilt rotor aircraft. However, for tilt rotor aircraft operating in a rotorcraft mode or in

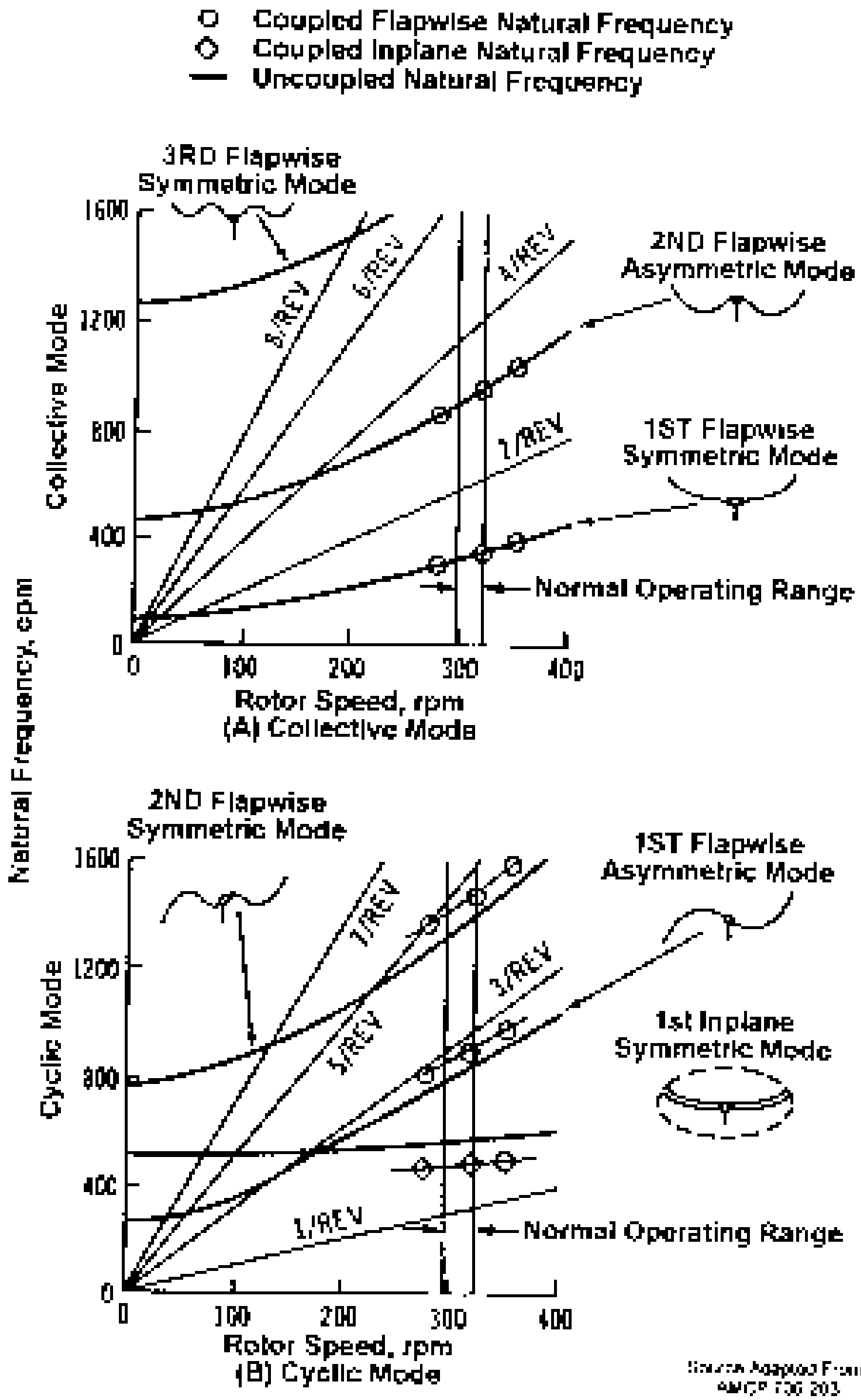


Figure 9-7 Typical Plots of Rotor Natural Frequency vs Operating Speed

transition between rotorcraft and aircraft with fixed wings, Regions I, II, and III requirements will apply, as appropriate.

Crew and personnel station vibration criteria for frequencies up to 60 Hz are identified in ADS-27 as are criteria for controls, instrument panels and displays, and weapons sighting devices. Additionally, ADS-27 identifies the requirement for new aircraft or aircraft undergoing major modification to incorporate onboard rotor vibration diagnostics systems. Demonstration and qualification of this onboard system is accomplished as part of the flight vibration surveys.

For aircraft the PA should specify in the Airworthiness Qualification Plan (AQP) flight vibration testing to be accomplished by the AC. The AC should define methods, conditions, analysis, and criteria for that testing in the AQS.

9-8 ACOUSTIC NOISE TESTS

Acoustic noise testing should establish an accurate definition of internal and external acoustic fields. Typically, it is a good idea to coordinate these test plans with the US Army Aeromedical Research Laboratory (USAARL) because this Laboratory is responsible for the review of data and input into health hazard assessments. These data are used to substantiate that specification noise requirements have been met. MIL-STD-1474, *Noise Limits for Military Materiel*, (Ref. 25) identifies the three types of noise criteria that may be used for limit noise exposure. These are hearing damage risk criteria (DRC), hearing conservation criteria, and materiel design standards. Of the three criteria materiel design standards provide specific noise limits to equipment designers and manufacturers that must not be exceeded if the materiel is to be acceptable to the PA.

Prior to acoustic noise testing the AC should have an acoustic noise survey that includes but is not limited to the external and internal noise conditions to be investigated, instrumentation and noise measurement requirements, test schedules, and data analysis requirements.

Measurements should be used to determine the acoustic environment with respect to established criteria. Such criteria include but are not limited to annoyance, distraction, speech interference, hearing damage, and external detectability.

9-8.1 INTERNAL NOISE TESTS

Internal noise testing should be conducted to obtain data that can be used to determine compliance with an established limit on the amount of noise permitted within the air vehicle. The limit may be based on hearing, speech communication requirements, effects on crew performance, and/or comfort level as specified by the PA. Information concerning these tests can be found in MIL-STD-1789, *Sound Pressure Levels in Aircraft*, (Ref. 26).

Since both the intensity and duration of noise contribute to noise exposure levels, noise intensity for all of the air vehicle operational modes should be determined. Used in conjunction with the time spent in each mode, sound levels for that mode can be used to calculate the noise exposure for a given mission profile.

For internal noise tests operational conditions that can be combined to form operational modes for testing include but are not limited to

1. Flight conditions analogous to the maneuvers of par. 9-4
2. Air vehicle configurations that affect noise attenuation, such as doors on or off and windows open or closed
3. Weapons firing status, active or inactive

4. Noise control means, such as soundproofing, installed or removed.

Minimum instrumentation requirements for internal noise tests should include but not be limited to

1. An instrumentation quality microphone or precision sound level meter (SLM) with free field and random incidence correction microphones
2. Calibration equipment for SLM to assure ±0.2-dB accuracy
3. Octave band analyzer (OBA) in accordance with American National Standards Institute (ANSI) Standard S1.11-86, *Octave Band and Fractional Octave Band Analog and Digital Filters, Specification for*, (Ref. 27)
4. Battery-operated tape recorder, if approved by PA
5. Environmental instruments, such as hygrometer and thermometer
6. Means to determine air vehicle altitude, velocity, power settings, and position of controls at the time of measurement
7. Signal cabling that will not generate spurious signals caused by vibration and electrical fields.

The AC should identify the internal noise criteria to be evaluated, instrumentation that will be used, methods of analysis and data reduction, and acceptable levels criterial.

9-8.2 EXTERNAL NOISE TESTS

External noise tests should be conducted to determine specification compliance, peak noise levels, spectral content, and sound directivity and should be sufficient to allow estimation of the probability of aural detection of the air vehicle. Another purpose of this test is to assess the damage risk criteria for ground personnel working in the air vehicle external noise field. Control of acoustic emissions is covered in subpar. 9-14.3.5.

Before testing begins the AC should identify the test site to be used. An idealized test site with a perfectly reflective plane surface may be used, or a site that simulates real-life conditions of terrain, ground cover, and weather may be chosen. Terrain should be uniform with a low sound-absorbing cover, and microphones should be positioned 1.5 m (4.92 ft) above the ground. In addition, the AC should identify methods for controlling extraneous ambient noise, and these methods should be used during testing.

The AC should select typical maneuvers from the maneuver spectrum discussed in par. 9-4 for external noise testing, and selected altitudes. As a minimum, these maneuvers should include IGE hover, flat pitch, and normal start and shutdown maneuvers in order to assess DRC for ground personnel.

The external noise tests should be conducted using equipment for noise data acquisition and analysis, for recording of meteorological data, and for electronic tracking, location, communication, and guidance of the air vehicle. Parameters to be measured include

1. Noise source strength and radiation
2. Temperature and wind velocity gradients and relative humidity
3. Scale and intensity of turbulence
4. Terrain geography and character and density of ground cover
5. Location of listening instruments.

The instrumentation used should include sufficient microphones, amplifiers, calibration equipment, electronic recording equipment, and time code generators to record the required parameters and correlate the recorded data with supporting data from other sources. The recording system should be able to record the frequency range of interest within 2 dB—usually 20 to 11,200 Hz. Time code generator outputs should be tied in with air vehicle position data, noise recordings, and possibly meteorological condition recordings. Layout, quantity, and spacing of microphones should be adequate to provide reasonable assurance that sideline noise characteristics are described and that unusual terrain or ground feature effects are considered.

During conduct of the testing, all noise data should be recorded for later laboratory analysis. The air vehicle should be flown at right angles to and over the center of the major axis of the microphone layout. These procedures and variations and piloting techniques, such as constant pitch flyovers, should be approved by the PA. Instrument calibration procedures should be documented.

Data analysis may involve the use of third-octave analyzers, narrow band analysis, pattern recognition devices, or a trained human ear. The methods used for data analysis and presentation including the use of automated and/or computerized hybrid analysis method integrating several analysis methods should be documented.

9-9 CLIMATIC LABORATORY TESTS

As part of the qualification tests, the entire air vehicle should be tested by operating the it (all systems including propulsion) in a climatic laboratory under controlled conditions that simulate as nearly as possible the operational conditions under which the air vehicle will operate. These conditions should be identified in the test plan, and should include but not be limited to temperature, shock, vibration, icing, sand and dust, and salt spray. Prior to qualification of the entire air vehicle, selected subsystems should be qualified in accordance with subpar. 6-2.6 for environments such as icing tunnels.

Climatic laboratory tests are essential to evaluating the effects of climatic conditions on

1. Airframe and dynamic component operation and strength
2. Engine operation and performance
3. Pilot capabilities
4. Operating characteristics of
   a. Windshield, engine, and rotor system anti-icing, deicing, and defog systems (windshield clear and ready for flight within specified time)
   b. Transmissions
   c. Avionic and control subsystems including cooling
   d. Auxiliary power units
   e. Fuel, electrical, and hydraulic or pneudraulic subsystems
   f. Heating, ventilating, and environmental control subsystems
   g. Maintenance procedures
   h. Handling and firing of external stores and weapons, if applicable.

Department of Defense (DoD) Directive 3200.11, *Major Range and Test Facility Base*, (Ref. 28) contains information on DoD test facilities available for all testing. The McKinley Climatic Laboratory, located at 3246th Test Wing, Eglin Air Force Base (AFB), FL, is the primary climatic laboratory used for this type of testing. Test planning for use of this laboratory must include a formal request by the PA to use the facility. Test planning by the AC is critical to the success of the climatic laboratory testing since the facility is heavily used and access is limited.

During the climatic laboratory testing, the air vehicle should be restrained by a system capable of absorbing maximum main rotor thrust or maximum propeller thrust. Exhaust gases from the APUs and cabin heaters and cooling exhaust from electronic and electrical components should be vented outside the chamber if these exhausts will have a significant effect on laboratory ambient temperatures. Electrical load banks for the electrical system should be used to ensure maximum generating capacity is used.

In the test plan the AC should identify the time requirements for temperature “soak” (usually 48 h), preflight inspection, APU check, and systems checkout procedures to be used prior to climatic testing. The AC should also identify the test sequence(s) to be used after main engine(s) start and the simulated mission profile to be tested.

Once main engines are started, the testing should follow the approved test sequence and applicable mission profile. Conditions that produce cracks or fluid leaks should be noted as the air vehicle “flies” the simulated mission profile(s). If minor repairs are made and time permits, tests should be repeated to verify repairs.

The AC should identify the limitations of the climatic laboratory testing in the test report. These limitations typically include

1. Effects of tie-down systems on load paths and vibration characteristics
2. Changes in airflow around a rotorcraft operating at high-power IGE
3. For larger air vehicles the effect of high power settings on chamber ambient temperature.

Although the climatic laboratory tests are good indicators of performance in extreme environments, the climatic laboratory cannot simulate all of the possible environments to which the air vehicle will be exposed. Consequently, climatic laboratory tests should be followed by actual operational tests in natural environments.

9-10 ICING FLIGHT TESTS

Icing flight tests might be required to verify the operational capability of the air vehicle in flight conditions conducive to ice formation. Some specifications do not require this capability. The air vehicle may contain anti-icing or deicing equipment or a combination of the two. Some air vehicle subsystems and components require protection from the effects of ice formation due to the possibility of damage or performance degradation due to ice. See 14 CFR, Parts 25 (Ref. 5) and 33 (Ref. 18), and Advisory Circular 29-2, *Certification of Transport Category Rotorcraft*, (Ref. 29) for additional information. Consequently, the air vehicle specification and AQS might require that the operational capability of the entire air vehicle be demonstrated through actual and simulated flight in icing conditions.

Factors that influence the degree of icing include liquid water content, droplet size, surface temperature, altitude, and airspeed. However, consistent natural icing conditions are difficult to obtain. Conversely, simulated environments are highly dependent on ambient conditions such as temperature, wind velocity, and gust factor; therefore, it is also difficult to obtain consistent results.

Test plans should be submitted by the AC to demonstrate the following characteristics:

1. Increase in power required to maintain given flight conditions as a function of accreted ice thickness
2. Capability of the engine air induction system to maintain airflow for full engine power capability and ensure that ice ingestion does not occur
3. Capability of the windshield or windscreen system to maintain visibility requirements, preclusion of damage when anti-icing or deicing systems are used on dry windshield or windscreen

4. Air vehicle controllability

5. Heat transfer system performance of the anti-icing or deicing system(s)

6. Possibility of structural damage when ice is shed

7. Vibration levels during deicing system cycling

8. Proper operation of all ice protection system equipment and controls.

There are three types of tests to be conducted. Clear, dry air flight, simulated icing flight, and natural icing flight tests requirements are discussed in the subparagraphs that follow.

9-10.1 CLEAR, DRY AIR FLIGHT

Functional, safety, and performance characteristics of each ice protection system in the air vehicle should be demonstrated in specified conditions. Therefore, test procedures should consider the maximum operational capability of each system, its controls, and protective devices.

The effects of operating hot air systems on both the power consumed and conditions of protected surfaces should be determined at approved power conditions and altitudes. Additionally, approved power and airspeed conditions should be used to demonstrate electrothermal ice protection systems. Emphasis should be placed on determining electrical power requirements and availability. If freezing point depressant liquids are used, distribution and control of the liquids should be demonstrated.

The effects on unprotected surfaces may be simulated by attaching icing shapes and weights to those surfaces. During these tests, flutter and stall characteristics and the effects of those buildups on drag and mission range should be determined.

9-10.2 SIMULATED ICING FLIGHT

If required by the PA, flight in icing conditions might be required. There are various DoD icing spray systems (ISS), including the helicopter ISS (HISS). However, this equipment cannot normally duplicate natural icing conditions but is a valuable aid in obtaining pilot observations on visibility, control, and icing buildup during hover and low-speed maneuvers.

For rotorcraft rotor blades and aircraft or tilt rotor propellers, tests should be conducted throughout the ice condition spectrum to ensure correct operation, determine cycling time, determine impingement surface limits, and detect ice thickness. An optimum system should ensure that

1. No runback or refreezing of melted ice occurs.

2. The deiced accretion will not cause structural damage or loss of performance when shed.

3. Any cycling time requirements as a function of the rate of ice accretion are established.

4. Ice buildup and shedding do not introduce unacceptable levels of vibration. The aircraft should also be tested with these subsystems off to determine the increased power required during given flight conditions as a function of accreted ice thickness.

9-10.3 NATURAL ICING FLIGHT

Unless otherwise specified in the contract, the AC should use Title 14 Code of Federal Regulations for guidance. 14 CFR, Part 25 (Ref. 5) should be used as guidance for aircraft icing qualification requirements. See Subpart 25.1093, *Air Induction Icing Protection*; Subpart 25.929, *Propeller Deicing;* Subpart 25.1403, *Wing Icing Detection Lights;* and Subpart 25.1419, *Ice Protection.* Also, unless otherwise stated in the specification, the AC should use 14 CFR, Part 33, (Ref. 8) for guidance, specifically Subpart 33.68, *Induction System Icing.* Advisory Circular 29-2 (Ref. 29) should be used as guidance for all rotorcraft. Natural atmospheric icing conditions differ from snow conditions. The PA might also require demonstration of the ability of the air vehicle to operate in falling or blowing snow; however, conditions for freezing water are not necessarily the same as those required for icing conditions.

The flight test program should progressively increase flight durations in snow conditions. Initially, short periods of flight should be conducted into icing clouds to obtain data on ice protection systems, power loss, and flying qualities. Flight time in icing conditions should be increased progressively to obtain full performance data. Extreme care should be exercised to ensure that excessive ice that would constitute an unacceptable hazard is not allowed to accumulate on the air vehicle during testing. Hazards to ground personnel, such as ice shedding during ground operations, should also be considered.

9-11 ELECTROMAGNETIC ENVIRONMENTAL EFFECTS (E3)

ADS-37-PRF, *Electromagnetic Environmental Effects (E^3) Performance and Verification Requirements*, (Ref. 30) should be used to establish subsystem- and system-level E^3 testing requirements for Army air vehicles. These testing requirements typically are driven by the expected operational electromagnetic environment (EME) and allowable E^3 effects established by the PA during the program preaward phase. System-level E^3 testing should consider the following areas:

1. Electromagnetic compatibility (EMC)
2. Electromagnetic vulnerability (EMV)
3. Lightning
4. Static electricity
5. Electromagnetic radiation hazards (RADHAZ)
6. TEMPEST.

The effects of nuclear electromagnetic pulse (NEMP), emissions control (EMCON), transient radiation effects on electronics (TREE), and directed energy weapons, such as high-power microwave (HPM), are discussed in par. 9-14.

ADS-37-PRF (Ref. 29) identifies the following four criticality types for evaluation of E^3 anomalies:

1. Flight critical
2. Flight essential
3. Mission critical
4. Mission essential.

Each anomaly identified during E^3 testing should be categorized into one of these criticality types.

An E^3 Requirements Board (E^3RB) or integrated product team, which typically is comprised of members from the program office, the user community, and the Aviation Research, Development, and Engineering Center, rules on categorization of equipment anomalies and determines which anomalies should be fixed and retested.

The subparagraphs that follow describe the requirements for system-level E^3 testing in greater detail.

9-11.1 ELECTROMAGNETIC COMPATIBILITY

The AC should conduct an intrasystem EMC test on a completely provisioned air vehicle (including ordnance) to demonstrate that the operation of one or more onboard subsystems or components does not result in degraded performance, unacceptable response, or malfunction of any onboard subsystem or component. Air vehicle subsystems and components should be exercised singly and jointly as they would be during typical mission scenarios. As a minimum, the AC should demonstrate acceptable performance characteristics during the following electromagnetic tests:

1. Ambient (background noise) measurement
2. Cross-talk (circuit isolation)
3. Receiver to receiver
4. Transmitter to receiver
5. Transmitter to active device
6. Transmitter to passive device *
7. Receiver to active device
8. Receiver to passive device*
9. Active device to passive device*
10. Active device to receiver
11. Electrical power system transients*
12. Electrical/electronic subsystem transients*
13. Simulated mission evaluation
14. Flight evaluation.

EMC testing should be conducted in an area of low ambient electromagnetic levels in order not to interfere with the test to be conducted. Electrical bonding measurements and functional testing of equipment should precede the EMC test to reduce risk of test failures or delays in testing. EMC effects with associated support systems, such as ground servicing equipment and ground support equipment (GSE), should also be considered during this testing. Additional testing methodology is provided by ADS-37-PRF (Ref. 30).

*These tests should include 16.5-dB safety margin testing of electroexplosive devices, which should verify that EED bridge wire currents due to the (cumulative) induced energy from onboard and external equipment are at least 16.8 dB below the “no fire” current levels of the EEDS.

9-11.2 ELECTROMAGNETIC VULNERABILTY

With AC support the PA should conduct an intersystem EMV test on a completely provisioned air vehicle including ordnance less EEDs to determine any degraded performance, unacceptable response, or malfunction of any onboard subsystem or component when exposed to an electromagnetic environment external to the air vehicle. As a minimum, the air vehicle should be exposed to the worldwide EME defined in ADS-37-PRF (Ref. 30) and further defined by the air vehicle E^3RB during the program preaward phase. Air vehicle subsystems and components should be exercised singly and jointly as they would be during typical mission scenarios. When a test anomaly is discovered, an attempt should be made to isolate it to the susceptible subsystem or component, and as time allows, a potential fix should be determined. The test report should include vulnerability thresholds of the anomalies noted, frequencies, modulations, aspect angles of radiation, and other details of the test setup so that test conditions could be repeated at a later date to produce the same anomalies. EMV of the associated ground servicing equipment and ground support equipment should also be considered during this testing. A buildup approach in test levels should be used to minimize risk of damage to air vehicle. Additional testing methodology is provided by ADS-37-PRF (Ref. 30).

9-11.3 LIGHTNING

The AC should conduct and/or support a PA-conducted lightning protection survey and verification as provided for in subpars. 4.1.2 and 4.1.5 of MIL-STD-1795, *Lightning Protection of Aerospace Vehicles and Hardware*, (Ref. 31). Detailed testing methodologies may be found-in MIL-STD-

1757, *Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware*, (Ref. 32) and ADS-37-PRF (Ref. 30). The types of tests that should be considered are addressed in the subparagraphs that follow.

9-11.3.1 Direct Effects Testing

A full-scale air vehicle generally should not be exposed to direct effects testing; rather, selected components should be tested based on an analysis of lightning attachment zones in conjunction with scale-model tests and/or other lightning test experience, including actual lightning strike statistics. Direct effects testing may be conducted either on coupons or samples of materials, such as those that characterize airframe skins, structural members or joints, and on full-scale production components that protrude into the airstream such as rotor blades, other airfoil tip areas, flight control linkage, weapons, antennas, sensors, and fuel systems, to name a few. Composite materials have replaced aluminum in secondary structures and in some cases, the primary structure. If the area inside the composite material is confined, the atmosphere inside the confined area could be superheated and cause an explosion. The pass-fail criteria, which should be established by the E^{3}RB during the program preaward phase, should be based on the ability to land safely, the ability to continue the mission, or to minimize the cost to repair.

9-11.3.2 Indirect Effects Testing

These types of tests may be conducted on a full-scale air vehicle with the goal of establishing the extent to which a direct strike to the air vehicle could couple unacceptable electrical voltage surges or transients into electrical or electronic subsystems installed in the air vehicle. A typical test involves the application of a high-level artificial lightning current between expected attachment points (See lightning strike zone analysis in MIL-STD-1795 (Ref. 31).) on the exterior of the air vehicle while resulting responses are monitored on the interior wiring. To minimize risk of damage to the air vehicle, test equipment, or to test personnel, the test should be conducted in incremental steps starting with minimum discernible induced current levels until the maximum applied threat level is attained. The pass-fail criteria should be based on induced transient data obtained during component electromagnetic interference testing (see subpar. 7-10.1).

9-11.3.3 Streamering Testing

The previously described lightning tests should also include a streamering test by which the exterior of the air vehicle or a mock-up portion of the air vehicle is subjected to a high-level electric field—a precursor to a possible lightning strike—to determine whether any arcing or sparking occurs to flight crew personnel, fuel vapors, ordnance, or flight-critical electrical or electronic equipment.

9-11.4 STATIC ELECTRICITY TESTING

The AC should conduct or support PA-conducted static electricity tests on a full-scale air vehicle. Testing should demonstrate

1. Ground personnel are not exposed to hazardous electrostatic discharges (ESD) during fueling, arming, and sling-load operations.
2. Precipitation static (P-Stat) is controlled in order not to degrade the performance of onboard electrical or electronic equipment.

9-11.5 RADIATION HAZARDS (RADHAZ)

The AC should conduct appropriate testing to demonstrate that the hazards of electromagnetic radiation to ordnance (HERO), the hazards of electromagnetic radiation to personnel (HERP), and the hazards of electromagnetic radiation to fuel (HERF) are sufficiently controlled in order not to endanger the air vehicle or its personnel or adversely impact mission performance.

9-11.5.1 HERO Testing

Information about the determination of HERO testing can be found in MIL-STD-1385, *Preclusion of Ordnance Hazards in Electromagnetic Fields, General Requirements for*, (Ref. 33) modified to a minimum of 20 O V/m to demonstrate that sufficient safety margin exists to preclude inadvertent ignition or dudding of ordnance EEDs due to the air vehicle external EME.

9-11.5.2 HERP Testing

HERP testing should be conducted to demonstrate that electromagnetic radiation hazards to onboard and ground personnel are controlled to appropriate levels. Electromagnetic radiation levels should comply with ANSI/IEEE C95.1-1991, IEEE *Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz,* (Ref. 34) as implemented by Department of Defense Instruction (DoDI) 6055.11, *Protection of DoD Personnel From Exposure to Radio Frequency Radiation and Military Exempt Lasers*, (Ref. 35). Onboard emitters should be jointly exercised to the extent they would be during typical mission scenarios.

9-11.5.3 HERF Testing

HERF testing should be conducted to demonstrate that sufficient bonding, grounding, and shielding exist to preclude inadvertent ignition of fuel vapors onboard the air vehicle caused by onboard electromagnetic emitters as well as the EME. Onboard emitters should be exercised jointly to the extent they would be during typical mission scenarios.

9-11.6 TEMPEST Testing

The AC should conduct or support PA conducted TEMPEST testing in accordance with contractual requirements.

9-11.7 ANTENNA COUPLING

Antenna-to-antenna coupling should be analyzed as part of the intrasystem EMC testing. Analysis should cover areas exposed by history of known problems in previous programs and areas suspected by the contractor to be problem areas. Emphasis should be placed on determining the effects of active transmission through one antenna on passive systems or receivers of another system. For information concerning intrasystem EMC testing, see ADS-37-PRF (Ref. 30).

9-12 WEAPON SYSTEM EFFECTIVENESS TESTS

Army air vehicles that incorporate armament subsystems should be subjected to qualification to validate compliance with the air vehicle specification requirements. Those subsystems include but are not limited to missile, aerial rocket, turreted and fixed guns, target acquisition and/or designation hardware and software, fire control and integration hardware and software, and boresighting subsystems. Any weapons subsystem change that represents a significant departure from existing designs or that embodies major features not previously tested should be tested to demonstrate compliance with the guidance of this handbook and the system specification. However, prior to any ground and flight testing, the armament and fire control subsystems must go through laboratory and hot bench tests to validate critical component and software parameters, component fabrication, and subsystem and software integration. Time line requirements should be verified. Inhibit, limit, and interrupt analyses should be conducted to show that armaments are prohibited from interfering with one another and to show that armaments are inhibited from firing when firing constraints are exceeded.

In all cases safety should be paramount in evaluation and demonstration of weapons systems. For additional guidance concerning range safety, refer to AR 385-63 (Ref. 36) and related 385 series regulations. The Airworthiness Qualification Specification should describe the scope, test planning, testing, instrumentation and data analyses, and documentation requirements for weapons and fire control subsystems installed on an air vehicle. Ground testing of these subsystems should encompass all items requiring verification prior to flight testing. Flight testing should include all applicable testing types necessary to verify the armament/fire control subsystem design prior to any required formal demonstrations. See ADS-20, Armament/Fire Control System Survey, (Ref. 37) for additional information.

Ground tests should include but not be limited to

1. Armament and fire control operations
2. Armament and fire control boresight
3. Arming procedures
4. Ground firing tests
5. Displays and display resolution
6. Sensor switching
7. Target acquisition and designation sight (TADS)
8. Laser designators, range finders, and laser spot trackers (LSTs)
9. Cryogenic cooling
10. Fire control integration
11. Boresight systems
12. Electromagnetic compatibility
13. Environmental conditions.

Prior to first flight, ground tests using air vehicle power should be conducted on the air vehicle. The purposes of these tests are to validate critical air vehicle interfaces, ensure EMI/EMC compatibility, verify safety-of-flight critical features, and ensure functionality of all operational controls and modes. Flight testing should be performed to verify the design and its integration prior to actual firing of stores. Flight testing of the armament and fire control subsystems should be conducted within the design operational flight envelope (OFE) for rotorcraft or the limit maneuvering envelope (LME) for other aircraft. The OFE is defined in ADS-33 (Ref. 22) and the LME is defined in 14 CFR Part 23 (Ref. 4). These flight tests should include but not be limited to

1. Air vehicle flight performance
2. TADS pointing and day or night, navigation, and target handover capability
3. Laser ranging and designation
4. Effects of weapons firing on TADS
5. External stores jettison
6. Gun, missile, and rocket operation, range, clearance cones, boresight retention, and accuracy
7. Fire control installation
8. External stores
9. Weapon firing effects on engine(s).

Information concerning ground and flight tests can be found in ADS-20 (Ref. 37).

The weapons subsystems configuration for effectiveness testing should be as near as possible to the production installation, including all nonfunctioning elements of the subsystem. Weapons systems effectiveness tests against ground and air targets are covered in subpars. 9-12.1 and 9-12.2, respectively.

Effectiveness measures for each of the subsystems should be specified by the PA, and in some cases measures of effectiveness (MOEs) may be dependent on several subsystems. These MOEs are used to verify that the delivered or proposed system meets the user's operational requirements.

In most cases these MOEs measured individually might not verify the effectiveness of the armament and fire control subsystem. Even if all MOEs are in compliance with specifications, the interaction of several characteristics may result in an armament and fire control subsystem that does not satisfy the user's requirements when used against ground or air targets.

To be effective against any target, the armament and fire control subsystem should allow the pilot, gunner, and/or weapons system operator to detect, classify, engage, and strike targets in vulnerable areas at maximum standoff ranges. Typical MOEs for these functions include but are not limited to

1. Probability of detection P_D of a particular target
2. Probability of classification P_C as to the correct type of target—hard or soft, wheeled or tracked
3. Probability of engagement P_E
4. Probability of hit P_H
5. Probability of kill P_K.

Many of these measures may be combined as conditional probabilities. Two examples are the probability of kill given a hit ($P_{K|H}$) and the probability of engagement given detection ($P_{E|D}$). Since the weapons system must detect, classify, engage, and hit the target to kill it, the total weapons system effectiveness E_W against a specific target at a given range using a specified armament subsystem can be expressed as:

$$E_W = P_D \cdot P_{C|D} \cdot P_{E|C} \cdot P_{H|E} \cdot P_{K|H}, \text{ dimensionless} \quad (9\text{-}4)$$

where

$P_{C|D}$ = probability of classification given detection
$P_{E|C}$ = probability of engagement given classification
$P_{H|E}$ = probability of hit given engagement.

Prior to any weapons system effectiveness testing, the integrated test plan should include a systematic ground and air test program necessary to determine weapons system effectiveness. This plan should describe the test, analysis, or simulation used to demonstrate the MOEs previously described and/or other MOEs specified by the PA . The plan should also include provisions for demonstration of safing and arming procedures both on the ground and in flight and should describe testing to verify that loading and unloading procedures can be accomplished safely.

Full-mission simulators should be used to address the total mission environment, which includes training, battlefield tactics, and environmental conditions. The full-mission simulator should use cockpit systems that demonstrate the capabilities of the proposed concepts under test and have the capability for the air vehicle to detect airborne and surface targets and geographical features visually at ranges that are representative of actual flight.

Instrumentation and data analysis should be based on ADS-20 (Ref. 37), and included in the armament and fire control portion of an overall integrated test plan.

9-12.1 GROUND TARGETS

Target acquisition and designation systems qualification against targets should include data points that exercise the required ranges of air vehicle parameters, sensor modes of operation, target parameters, and meteorological conditions. See ADS-29 (Ref. 37) for additional information. Obscurants such as fog, haze, smoke, or light rain may reduce detection capability P_D at maximum weapon ranges. Clutter might reduce probability of detection, classification, and engagement of targets—P_D, P_C, and P_E, respectively. Effectiveness testing against ground targets should consider the effects of clutter and smoke and obscurants on MOEs such as reduced P_D, P_C, or P_E, and these results should be documented.

Moving targets or targets that change directions might reduce P_H for unguided weapons such as guns and rockets. For guided weapons the ability of the weapon subsystem to track the vulnerable areas of a target until round impact should be evaluated. Inability to track these areas might result in a miss or impact in other than a vulnerable area, which results in reduced P_H and P_K, respectively. The maneuvering required in unmasking might result in detection of the air vehicle or might preclude timely engagement of the ground target. Both of these conditions could allow the target to initiate evasive action or mask itself.

The effects of target motion and direction changes and unmasking maneuvering of the air vehicle on MOEs, such as P_E, P_H, and P_K, should be documented.

9-12.2 AIR TARGETS

The same considerations for ground target effectiveness should be used when weapons system effectiveness against air targets is evaluated. However, since air targets might have equal or superior maneuverability and comparable or superior armament and fire control subsystems, certain aspects of weapon system effectiveness testing become more important. The armament and fire control test planning should define the methods used to verify operational characteristics of weapons subsystems when used against air targets. These methods should be included as part of an overall integrated test plan. The operational characteristics are specified by the PA, and these tests, models, or simulations should use a firing envelope approved by the PA. Typical firing envelope parameters should include airspeed, maneuver load factors, and time to turn and engage off-axis targets. A safe launch envelope should be defined by analysis and actual firing.

Sensor gimbal limits and turreted gun azimuth and elevation limits are demonstrated throughout the firing envelope. Additionally, sensor and turret slew rates, accelerations, and position accuracies should be demonstrated throughout the firing envelope. The AC should demonstrate the proper function of limit switches, such as a gun-firing inhibit, when either the sensor or turreted gun is commanded to point or fire outside the established limits for position, slewing rate, or acceleration.

In addition to the probability MOEs (P_D, P_C, etc.), false alarm rates should be demonstrated when there is a requirement for engagement of air targets beyond visual range (BVR).

Handling qualities when firing armament should be evaluated. Particular emphasis should be placed on off-axis gun firing, maximum and minimum elevation or depression of turrets, and missile and rocket firing during uncoordinated flight. Emergency jettison of external armament stores should be demonstrated throughout a Government-approved flight envelope.

9-13 EXTERNAL STORES SEPARATION

Flight tests should be conducted to demonstrate the separation characteristics of all droppable external stores. Droppable external stores are defined as any item that is not an essential part of the basic air vehicle and is affixed to the airframe with provisions for quick release. Droppable external stores may include but are not limited to fuel tanks, weapons pods, rocket launchers, missile launchers or rails, bombs, mine dispensers, torpedoes, or pyrotechnic devices.

Satisfactory separation characteristics should be demonstrated for the minimum criteria that follow and other criteria that may be specified by the PA:

1. Immediate operation of the jettison device or operation within an allowable time period
2. No damage to the air vehicle during or following actuation of the jettison device
3. Jettison trajectory clear of the air vehicle and other stores
4. No inherent instability of the jettisoned store while in proximity to the air vehicle
5. No adverse or uncontrollable air vehicle reaction at the time of jettison
6. Stability and control characteristics after jettison consistent with ADS-33 (Ref. 22) for rotorcraft and tilt rotor aircraft and 14 CFR Parts 23 and 25 (Ref. 4 and 5) or other specified documents for aircraft
7. No unusual degradation of performance characteristics after jettison.

Jettison of all external stores should be demonstrated for sufficient combinations of flight conditions to establish and verify a jettison envelope for each type of external store configuration. Selective jettison of stores should be demonstrated for those conditions that may result in adverse operational characteristics of the air vehicle and the remaining external stores. Typically, safe jettison is almost always demonstrated by limited jettison tests in conjunction with extensive jettison analysis.

All jettisons use the release method provided. However, each secondary or redundant release system should be used once during these demonstrations. All system failures should also be shown not to affect adversely the air vehicle characteristics or the jettison capability of the remaining stores.

Flight conditions for jettison demonstrations should be planned and documented. All demonstrations should be conducted at the extreme or critical combinations of weight and both longitudinal and lateral CG locations within the air vehicle maneuver spectrum. When external stores have expendables, such as rockets and flares, separation is demonstrated with full, intermediate, and empty weights for the stores.

Jettison demonstrations should be performed at sufficient airspeeds to establish the airspeed restrictions for satisfactory separation characteristics and demonstrated at the power required for level flight and during autorotative flight or unpowered glide. The maximum and minimum airspeed limits for safe operations should be established. Demonstrations should be conducted at altitudes and attitudes consistent with normal operation of the air vehicle. If the attitudes of external stores with respect to the air vehicle are varied, the most critical attitude consistent with operational usage should be demonstrated.

The initial envelope of sideslip as a function of airspeed should be determined from the side force stability parameter d φ/dβ where φ is the bank angle and β is the sideslip angle, and the side force required to recognize uncoordinated flight. The side force stability parameter is obtained during stability and control testing as a function of calibrated airspeed. During initial testing, the side force required to recognize uncoordinated flight can be determined. This side force requirement fixes an equivalent bank angle, which, when applied to the side force stability parameter, yields a limit sideslip angle as a function of calibrated airspeed as shown in Fig. 9-8. This figure shows how to determine the initial jettison sideslip envelope limit that should be demonstrated.

Video recording should be used to document the separation characteristics of all external stores configurations. Still photography should be used to document the location, shape, and method of attachment of external stores and the damage to the air vehicle caused by jettison. In addition to video, jettison testing should include data acquisition systems that are similar in nature to those required for the flying qualities test of subpar. 9-6.2.

9-14 SURVIVABILITY

Department of the Army (DA) Pamphlet 71-3, *Operational Testing and Evaluation Methodology and Procedures Guide*, (Ref. 38) defines survivability as the degree to which a system is able to avoid or withstand a hostile environment without suffering abortive impairment of its effectiveness—its ability to accomplish its designated mission. DoD Regulation 5000.2, *Mandatory Procedures for Major Defense Acquisition Programs (MDAPs) and Major Automated Information System (MAIS) Programs*, (Ref. 39) states that survivability considerations form the basis for sustaining operational effectiveness and war fighting capability in peacetime and at all levels of conflict (from low intensity to strategic nuclear) through acquisition of survivable systems, equipment, and support. Threats considered should include conventional; electronic; initial nuclear weapon effects; nuclear, biological, and chemical (NBC) contamination; advanced threats such as high-power microwave, kinetic energy weapons, and directed energy weapons, terrorism, and sabotage.

The AC is totally responsible for satisfying the survivability performance requirements. The means by which to satisfy these requirements should be determined by the AC and included in the overall program plan and AQS. ADS-11, *Survivability Program, Rotary Wing*, (Ref. 40) can be use as a source of information. The survival characteristics of the air vehicle should be optimized so that the system meets the requirements of the specification at the least cost. The tradeoff process includes examining and quantifying both the survival benefits and penalties associated with alternative survivability enhancement techniques.

DA Pamphlet 71-3 (Ref. 38) describes some of the measurements used to assess survivability. These measurements include vulnerability, susceptibility, and avoidance capabilities. ADS-11 (Ref. 40) provides a more detailed definition of the

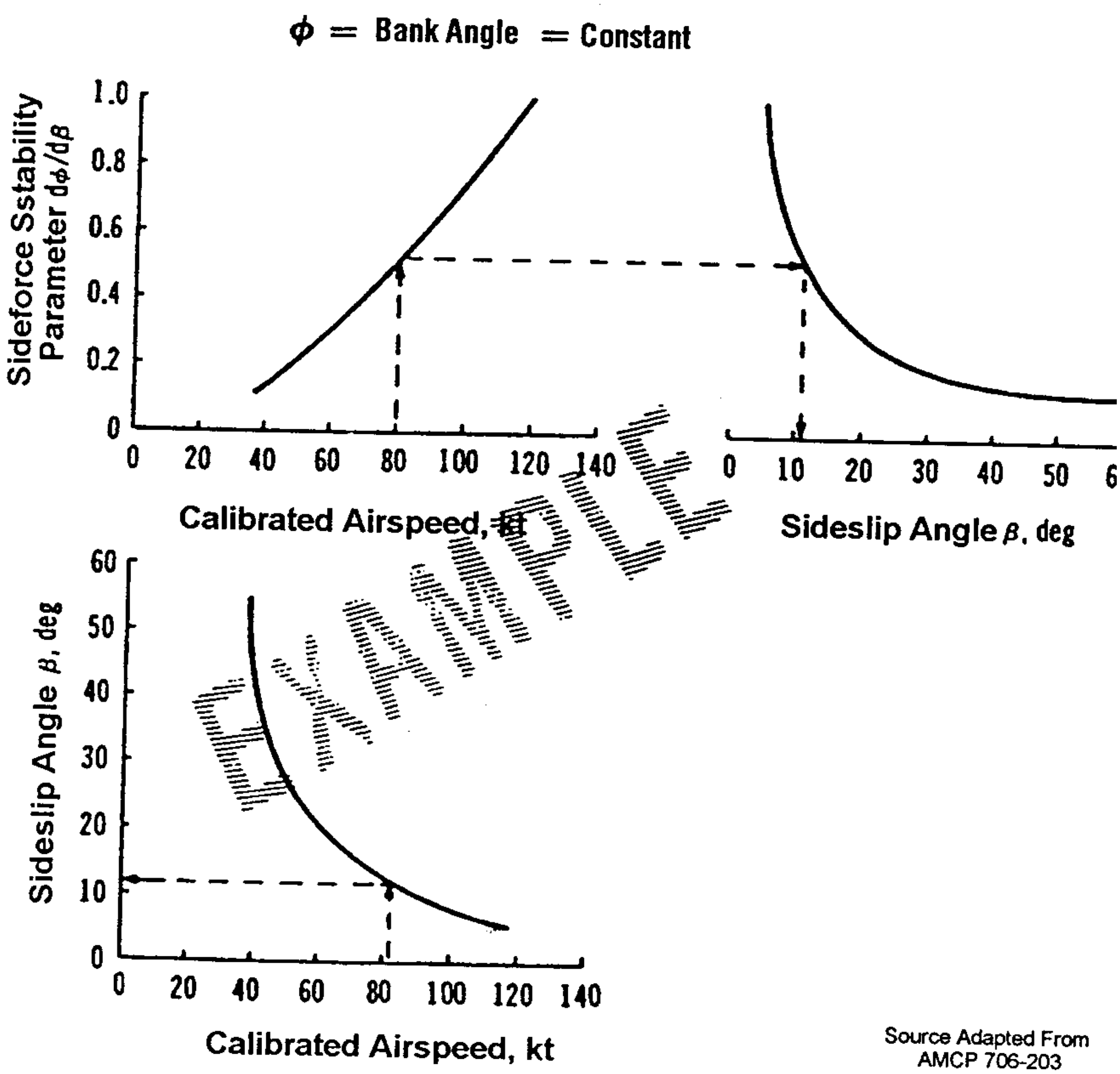


Figure 9-8 Jettison Envelope Calculation

ballistics, directed energy, nuclear, and NBC hardening; analyses; and test requirements as well as crashworthiness analyses and testing. DoD Regulation 5000.2 (Ref. 39) also includes provisions for survivability of mission-critical electronic equipment in an electronic countermeasures environment.

The probability of kill P_K is

$$P_K = P_D \cdot P_{C|D} \cdot P_{E|C} \cdot P_{H|E} \cdot P_{K|H},$$ dimensionless (9-5)

and the probability of survival Ps is

$$P_S = 1 - P_K,$$ dimensionless (9-6)

where

P_{D}	=	probability of detection by a particular threat at the specified range
$P_{C\|D}$	=	probability of classification given detection by the threat as the correct type of target
$P_{E\|C}$	=	probability of engagement given classification
$P_{H\|E}$	=	probability of hit given engagement
$P_{K\|H}$	=	probability of kill given a hit.

If an acceptable value for probability of survival is 0.965, then individual values of 0.5 for the probabilities in Eq. 9-5 would satisfy the criteria

$$P_{K} = 0.5 * 0.5 * 0.5 * 0.5 * 0.5 = 0.03125$$

and

$$P_{S} = 1 - 0.03125 = 0.96875.$$

As can be seen from Eq. 9-5, if all of the probabilities start at 0.5, then an increase of 0.1 in any of these individual probabilities may be counteracted by a decrease of 0.0833 in another. P_{S} should be measured considering all of the combined effects because all factors are interdependent.

9-14.1 BALLISTIC SURVIVABILITY

DoD Regulation 5000.2 (Ref. 39) cites Title 10, United States Code, Section 2366, "*Major Systems and Munitions Programs: Survivability Testing and Lethality Testing Required Before Full-Scale Production*", which requires live-fire testing of Acquisition Category I and II programs. Ballistic survivability testing is a major element necessary to satisfy this requirement. However, prior to any actual firing tests, analyses should be performed to the maximum extent possible to identify vulnerable components and subsystems in order to maximize the efficiency of live-fire testing.

Four elements of ballistic survivability testing are explained in the subparagraphs that follow. These elements are armor, ballistic-tolerant structure, positioning and separation of subsystems, and fuel ballistic protection. The testing to verify ballistic survivability should be identified in the Survivability Program Plan and should ensure that the air vehicle and crew can survive damage caused by specified threat munitions.

Threat projectile, impact location, obliquity, tumble, and striking velocity should be specified in test plans and should be recorded and reported for all firing tests. Information for this purpose can be found in ADS-11 (Ref. 40).

9-14.1.1 Armor

Several air vehicle components are both vulnerable to small arms fire and flight or mission essential. Armor is sometimes used to ensure that if these components are hit by small arms, mission accomplishment will not be precluded. Particularly vulnerable hardware includes engines, fuel cells, pumps and controls, hydraulic and/or pneudraulic components, transmissions, and control linkages and surfaces because they frequently cannot be masked by less critical components. However, use of armor should be minimized to prevent unacceptable performance degradation.

Prior to any survivability design or testing activities, the AC and PA should agree on the air vehicle damage measures to be applied. Typical measures are attrition, mission abort, and forced landing kills, as defined in MIL-STD-2089, *Aircraft Nonnuclear Survivability Terms*, (Ref. 41). Tradeoff analyses and cost-effectiveness analyses should also be performed. Information concerning these analyses can be found in subpars. 5.2.8 and 5.2.9 of MIL-STD-2069, *Requirements for Aircraft Nonnuclear Survivability Program,* (Ref. 42).

Information concerning ballistics vulnerability analyses, ballistic hardening, and ballistic testing can be found in ADS-11 (Ref. 40). Testing and analyses should be conducted against the threats identified in the system specification and/or AQS. Testing methods, munitions used, and passing criteria such as kill category, failure during damage tolerance testing, and $P_{K|H}$, should be identified in the test plan.

Compatibility of armor with operators and maintainers should be demonstrated. The AC should demonstrate that armor installed in its normal position does not interfere with critical operator or maintainer tasks.

9-14.1.2 Ballistic-Tolerant Structure

Components and structures designed to continue their functions after ballistic impact should be tested to determine their structural and functional characteristics after impact. These items should be identified by the AC. These components and structures should be subjected to postdamage testing. Information concerning this testing can be found in subpar. 5.2.1.2b of ADS-11. If battle damage assessment and repair (BDAR) is a requirement, such repairs should be tested to demonstrate specification compliance.

Degradation effects should be expressed in operational terms such as airspeed, “g” loads, angle of bank limits, and hours allowable after BDAR whenever possible.

9-14.1.3 Positioning and Separation of Subsystems

Positioning of components and subsystems can enhance survivability by reducing the vulnerable area of the air vehicle. Ballistic protection analysis is generally conducted by calculating the vulnerable area. The vulnerable area A_{Vi} for an individual component or subsystem is computed from

$$A_{Vi} = P_i A_i \text{ , m}^2 \text{ (ft}^2\text{)} \quad (9\text{-}7)$$

where

A_{Vi} = vulnerable area of the *i*th component or subsystem, m ^{2} (ft^2)

P_i = probability of damage per hit on the *i*th component or subsystem, dimensionless

A_i = presented area of the *i*th component or subsystem, m ^{2} (ft^2).

Noncritical components or subsystems have no vulnerable areas by definition. Therefore, if critical components can be masked by noncritical components and thus require the round to pass through the noncritical component, P_i will be reduced, and this reduction will reduce A_{Vi}. In addition, P_i will be reduced when the critical component is placed behind ballistic-protective panels. Summation of vulnerable areas for critical components for a single shot provides the total air vehicle vulnerable area for that particular shot.

ADS-11 (Ref. 40) provides procedures the AC can use to describe ballistic survivability design features. Included are provisions for technical descriptions that show critical components and subsystems, presented or projected areas, substantiation of claimed invulnerabilities, and analysis and tabulation of vulnerable areas.

When redundant components are used and loss of one or more redundant components would not result in a loss of a critical function, physical separation of the redundant components lessens the probability of a single-shot kill.

Methods of validation and testing for the vulnerable areas should be planned and documented including the analysis, ballistic testing, and simulations to be used.

9-14.1.4 Fuel Ballistic Protection

Fuel system ballistic protection evaluation is usually performed by firing at the air vehicle, air vehicle mock-ups, or subsystem components. Information concerning fuel system testing including tanks, plumbing, surrounding airframe and protective features, and crash resistant fuel tanks can be found in ADS-11 (Ref. 40). Additional information concerning crashworthy fuel tanks can be found in MIL-T-27422, *Tank, Fuel, Crash Resistant, Aircraft*, (Ref. 43). Emphasis should be on self-sealing and fire suppression procedures. Fuel system test plans should define the location and number of shots, obliquity, type of seal allowed after firing, caliber of rounds, post shot inspection requirements, and fire suppression requirements. If fuel cell or ullage inerting, such as onboard inert-gas-generating system (OBIGGS), is used, procedures for testing such features should be included. Both passive and active fire suppression techniques, as defined in MIL-STD-2069 (Ref. 42), are demonstrated as applicable.

9-14.2 LASER SURVIVABILITY

Vulnerability of the air vehicle and crew to both low-energy and high-energy lasers (HEL) should be demonstrated by the AC when laser weapons are included among the specified threats. Techniques for laser vulnerability reduction often follow the same guidelines as ballistic vulnerability reduction, such as providing redundancy, separation, and burnthrough tolerance. The specified threat and operating conditions should be used to identify the operating frequencies, types, power levels, pulse rate and duration, beam size, power distribution, and slew rates to be tested. Primary emphasis should be on protection of aircrew vision and optical systems from the effects of low-energy lasers and protection of all systems and the air crew from the effects of HEL. Each of these areas is covered separately in the subparagraphs that follow. Also information concerning these areas is included in ADS-11 (Ref. 40).

9-14.2.1 Optical Countermeasures

Typically, optical countermeasures are intended to protect sensitive electro-optic mission equipment and aircrew vision from the effects of low-energy lasers. Such equipment might include canopy transparency and optical coatings and/or laser-protective visors. Analysis should be performed to identify vulnerable components, subsystems, and air crew positions in a manner similar to the ballistic vulnerability analyses. Information about performing this analysis can be found in ADS-11 (Ref. 40). Emphasis should be placed on determining the vulnerability of the aircrew to temporary or permanent blindness or other debilitating injury caused by lasers. Measurable parameters may include but not be limited to exposure times, ranges, frequencies, and power levels required to damage electro-optics or injure aircrews. Evaluation of the optical countermeasures should also include evaluation of visual impairment of the pilot while operating with these devices or systems during night flight and/or with environmental obscurations. Also see par. 9-17.

9-14.2.2 High-Energy Lasers

High-energy lasers can damage the air vehicle system by several damage mechanisms similar to ballistic damage and by low-level heating of large areas. For each threat and critical component or subsystem, analyses should be conducted by the AC to identify the particular damage mechanism. Information concerning these analyses can be found in ADS-11 (Ref. 40). Component and subsystem testing for high energy laser susceptibility should also be conducted. This testing should include tests on ground test vehicles, static test articles, air vehicle sections, or full-scale operational air vehicles. Laser systems used should be identical to the threats considered without scaling for test purposes. Laser characteristics, test conditions, configurations tested, and results of the tests should be documented. Also see par. 9-17.

9-14.3 SIGNATURE CONTROL

Signature control of IR, electromagnetic, visible, acoustic emissions and radar can be an effective way to enhance air vehicle survivability. Reduced signatures can mean lower $P_{\boldsymbol{D}}$, $P_{\boldsymbol{C|D}}$, $P_{\boldsymbol{E|D}}$, and $P_{\boldsymbol{H|E}}$. These signatures should be calculated by computer simulation or analysis but if required for specification compliance by the PA, they may be subject to verification by flight testing. With the exception of acoustic signatures, all signatures are dependent on detection of electromagnetic emissions or reflections in some portion of the electromagnetic spectrum.

If required by the PA, the results of signature testing should be used to calculate the survivability of the aircraft when facing specified threat systems.

9-14.3.1 Infrared

IR signature testing should be conducted to measure the system IR signature and to determine specification survivability parameters. Testing is normally conducted in three phases: ground operation, hovering operation, and a flyby. Calibration of test equipment should be accomplished prior to and after each test phase. Ground and hovering operations should be used to collect data to plot radiant intensities in specified IR wavelength bands. These radiant intensities, usually expressed in W/sr, can be used to determine acquisition and lock-on ranges for specified threats. Once these intensities have been determined, flyby operations against actual or simulated threat systems should be used to verify these ranges.

The test methods and conditions to be used should be identified. Aspect angles, altitudes, and slant ranges are typical conditions to be specified. Primary and secondary IR radiation sources should be identified during ground and hover operations by incremental azimuthal measurement of IR signature through a 360-deg rotation of the air vehicle. Typical sources may include engines, cooling fans, and solar radiation reflected from the airframe.

Flyby testing should be conducted while the air vehicle is using maximum continuous power. Flight grids should be established and documented. Flyby testing should be conducted using an actual or simulated missile threat system that can measure radiometric data.

Since engine and ambient temperatures, atmospheric conditions, and solar radiation may have a marked effect on IR signature, certain measurements are required during this testing. These measurements include but are not limited to

1. Engine parameters of measured gas temperature (MGT) and gas producer and power turbine speeds, $N_{\boldsymbol{g}}$ and $N_{\boldsymbol{p}}$, respectively

2. Ambient temperature
3. Ambient pressure
4. Ambient humidity
5. Tailpipe or IR suppressor surface temperature
6. Pertinent fuselage temperatures affected by exhaust or secondary IR sources.

Data analysis techniques should be included in planning and documentation. As a minimum, measured spectral data should be compiled and the background data should be subtracted to obtain absolute signature data. The spectral data should be analyzed using computer analysis techniques to determine the acquisition and lock-on ranges of specified threat systems. Additionally, all parameters, such as MGT, temperature, and humidity, will be corrected to apply to the same atmospheric and aircraft conditions.

9-14.3.2 Radar Cross Section (RCS) and Signature

If required by the PA as part of the system specification, RCS signature control should be addressed by the AC in the testing program. Information concerning RCS reduction can be included in MIL-STD-2069 (Ref. 42). Analyses and testing should include the effects of external or mission stores on RCS. Primary measures may include but are not limited to jamming-to-signal (J/S) ratios for each aspect angle and threat combination required. The number and orientation of aspect angles, other test conditions, and the use of scale model tests should be planned and documented. Full-scale air vehicle or model tests should be used to obtain test results to verify specification compliance.

The minimum test conditions to be specified should consider air vehicle use, area of operations, probability of encountering each type of enemy radar, and mission profile(s). Using these conditions, the AC should identify the radar frequencies to be used, type of electrical and flight tests, maximum acceptable reflectivity, and reflectivity standard. These conditions should be identified along with hovering altitudes used or in the case of an aircraft, which cannot hover, heights and distances to be flown in a multilegged cloverleaf pattern. All test results should be reduced to decibels, which then can be referenced directly to the agreed-upon reflectivity standard. Typical standards include the sphere, the corner reflector, and the flat plate.

9-14.3.3 Electromagnetic Emission

Certain communication and navigation electronic subsystems might reveal the presence or aid in classification and engagement of an air vehicle. Such systems include but are not limited to onboard radar, Doppler navigation systems (DNS), radar altimeters, and communication subsystems. When these subsystems are used indiscriminately, the probabilities of detection, classification, and engagement (P_D, P_C, and P_E, respectively) may be increased.

Testing should involve assessment of P_D, P_C, and P_E for specified threats or threat simulators at various ranges. If emissions control is a requirement, these tests should be conducted in normal and EMCON mode. Maneuvering flight should be conducted during the tests if maneuvers can be shown to effect P_D, P_C, and P_E.

9-14.3.4 Visible Emission

If reduction of visible emissions is a specification requirement, the AC should demonstrate that visible emissions are at levels which comply with the system specification. Typical measures of visible signature are luminance and chromaticity. Luminance is defined as the luminous intensity of a surface in a given direction per unit of projected area, and chromaticity is the quality of color characterized by its dominant or complementary wavelength and purity taken together. Luminance may involve reflected light, such as sunlight glinting off canopy surfaces, or luminance of cockpit displays to outside observers. Normally, chromaticity requirements are satisfied by paint or paint schemes that blend with the surrounding terrain.

The testing methods, measurement techniques, and criteria used to measure visible emissions should be identified by the AC and approved by the PA.

9-14.3.5 Acoustic Emission

Acoustic signatures are the unique sound characteristics of the air vehicle that can be used for detection purposes. Par. 9-8.2 discusses air vehicle external noise testing. However, acoustic detectability depends on more than acoustical factors. A site that simulates real-life conditions of terrain, ground cover, and weather should be chosen. If the planned external noise tests conditions are the same, then combined tests may be proposed. Acoustic testing measures the frequency ranges and decibel levels produced by the air vehicle during specified maneuvering flight.

Microphones should be positioned 1.5 m (4.92 ft) above the ground for ground detection testing and near the tops of vegetation for testing overforested terrain. In addition, the AC should identify and use methods to control extraneous ambient noise, such as noise from rustling leaves.

The AC should select typical maneuvers from the maneuver spectrum discussed in par. 9-4 , altitudes, and piloting procedures to be used for acoustical emissions testing.

The acoustical emissions testing should be conducted using equipment of par. 9-8 for noise data acquisition and analysis, recording of meteorological data, and electronic tracking, location, communication, and guidance of the air vehicle. Parameters to be measured include

1. Temperature and wind velocity gradients and relative humidity
2. Scale and intensity of turbulence
3. Terrain geography and character and density of ground cover
4. Location of listening instruments.

Instrumentation used includes sufficient microphones, amplifiers, calibration equipment, electronic recording equipment, and time code generators to record the required parameters. The recording system will be able to record within 2 dB the frequency range of interest—usually 20 to 11,200 Hz. Time code generator outputs should be tied in with air vehicle position data, noise recordings, and possibly meteorological condition recordings. Layout, quantity, and spacing of microphones should be adequate to provide reasonable assurance that sideline noise characteristics are described and that unusual terrain or ground feature effects are considered.

During conduct of the testing, all acoustical emissions data should be recorded for later laboratory analysis. The air vehicle should be flown at right angles to and over the center of the major axis of the microphone layout. These procedures and variations, and instrument calibration procedures should be documented.

Data analysis techniques may be similar to the analysis techniques used to conduct external noise test. However, the methods used for data analysis and presentation should be identified.

9-14.4 MANEUVERABILITY

An air vehicle that can perform nap-of-the-earth (NOE) flight can reduce P_D for all radar and infrared guided weapons. Additionally, NOE flight shortens possible engagement time lines for unguided small arms threats. Thus maneuverability of the air vehicle system enhances P_S.

Once detected, a highly maneuverable air vehicle can reduce $P_{C|D}$ and $P_{E|C}$ and in some cases $P_{H|E}$ by executing evasive maneuvers. Par. 9-6 contains a detailed discussion of the aerodynamic demonstration requirements including the establishment of flying qualities.

The minimum maneuvers used to evaluate the maneuverability effects on survivability should be specified by the PA and should be used to verify air vehicle survivability equipment (ASE) effectiveness testing described in subpar. 9-14.5. Additional maneuvers may be identified by the AC.

Typical measures of effectiveness for maneuverability may include reduction in probabilities of detection, classification, engagement, and hit—P_D, P_C, P_E, and P_H, respectively.

9-14.5 AIRCRAFT SURVIVABILITY EQUIPMENT (ASE)

ASE basically can be categorized as threat sensors and countermeasures. Examples of ASE are IR jammers, radar jammers, radar warning receivers, and decoys. Additional survivability features that can aid defeat of threats by using the electromagnetic spectrum include low reflective paint and IR exhaust suppressors. Only the first four examples are described here.

IR jammers are intense IR sources that operate from the fuel or electrical power and confuse or decoy threat IR guided missile systems. When used in conjunction with low reflective paint and IR exhaust suppressors, these jammers jam all known threat IR missile systems.

Radar jammers are receiver-transmitters that detect both pulse and continuous wave (CW) illuminator radars and transmit jamming signals that prevent proper operation of enemy radar. Pulse illuminator radar jammers are designed to respond to the most critical threat weapons systems anticipated to be encountered by attack rotorcraft in a hostile environment, whereas CW radar jammers protect against surface-to-air missiles (SAM) and airborne intercept missiles (AIM).

Radar warning receivers also are designed to provide warning of pulse and CW illuminator radars before the air vehicle arrives in detection range. Additionally, there are missile approach detectors that detect the approach of IR guided missiles.

Decoys take the form of flares dispensed to confuse or mislead IR guided missiles and chaff dispensed from canisters or cartridges, which prevent radar-controlled air defense weapons from locating, hitting, and destroying the air vehicle dispensing chaff.

The AC should plan to conduct ASE effectiveness testing including use of the threat systems or simulators to be provided by the PA. Prior to testing ASE, the AC should establish the baseline susceptibility or vulnerability of the air vehicle to specified threat weapons systems when not using ASE. This should be done initially by analysis and verified by flight test using controlled maneuvers, altitudes, and air vehicle configurations. Typical measures are $P_{C|D}$, $P_{E|C}$, and possibly an analytical determination of $P_{H|E}$ without use of ASE. Threat systems or threat simulators should be used to establish the baseline characteristics and to perform effectiveness testing.

Once the baseline characteristics are established, the AC should repeat the flights and testing necessary to determine the reduction in susceptibility or vulnerability (increase in survivability) due to the use of

ASE. The AC should also document any limitations, such as electrical power, maneuvering, or range, brought about by use of ASE.

9-14.6 NUCLEAR, BIOLOGICAL, CHEMICAL (NBC)

Nuclear, biological, and chemical contamination survivability is defined as the capability of a system and its crew to withstand an NBC-contaminated environment and relevant decontamination without losing the ability to accomplish the assigned mission. NBC contamination survivability and testing should not be required unless it is reflected in the Operational Requirements Document (ORD) and Test and Evaluation Master Plan (TEMP) (Ref. 39). If a system requires NBC survivability, the AC should address each environment in an integrated test plan for the system. If required by the PA, contamination and decontamination survivability should be demonstrated for both short-term and long-term effects on materiel and personnel. Testing should also determine the degradation in operator performance due to operation in an NBC environment. A typical measure of effectiveness may be the percent of critical operator tasks successfully completed while wearing individual protection equipment (IPE) with a goal of 100%.

The total system should also be tested to determine the degree to which design features, such as cockpit overpressure and sealing, filtration systems, and hybrid collective protection equipment (HCPE) enhance NBC survivability of the operators. Information concerning these topics can be found in ADS-11 (Ref. 40).

9-14.7 DIRECT NUCLEAR EFFECTS

Nuclear survivability is defined as the capability of a system to accomplish its mission during and/or after exposure to a nuclear environment. Survivability may be achieved by a number of methods including but not limited to proliferation, redundancy, avoidance, reconstitution, deception, and hardening. Proliferation and platform redundancy are probably not viable options for relatively expensive and complex aviation systems. Avoidance and deception are tactical and/or strategic considerations. Thus hardening and subsystem redundancy are the only probable technical means by which to improve nuclear survivability for Army aviation systems.

Nuclear hardness is defined as a quantitative description of the resistance of a system or component to malfunction (temporary and permanent) and/or degraded performance induced by a nuclear threat environment. Hardness is measured by resistance to physical quantities such as overpressure, peak velocities, energy absorbed, and electrical stress. Damage mechanisms to be considered include blast, thermal, and initial radiation effects, and transient radiation effects on electronics (TREE).

Hardness requirements should be specified in the air vehicle specification, and validation requirements should be specified in the AQS. As a minimum, mission critical electronic equipment should be tested to verify survivability when exposed to high-altitude electromagnetic pulse (HEMP). Information concerning performing nuclear hardening analyses and testing for components and complete systems can be found in ADS-11 (Ref. 40).

9-14.8 CRASHWORTHINESS

The AC should demonstrate by analysis and testing the crashworthiness of the air vehicle. Normally, analyses are acceptable in lieu of actual tests, except at the component level. Structural crashworthiness, crew and passenger retention, injurious environment, postcrash fire potential, and evacuation should be the main considerations.

Appendix I of ADS-11 (Ref. 40) contains rating criteria for these areas as well as details of how the evaluation is performed. If required by the AQS, crashworthiness testing may be performed by the PA and AC. Details of that testing are included in subpar. 11-6.2. Data from AC testing should be used to reduce required Government testing.

9-15 AVIONICS—CONTROLS

The fundamental classification of flight control systems should be based upon whether control is automatic or manual. Whether control forces are transmitted through mechanical linkage, electrical wires, or fiber-optic cables does not greatly influence the task of flight control system qualification at the system level. The level of safety associated with manual or primary flight controls is established through proper design, analysis, and qualification of the individual components. Also software design and qualification begin at the unit level. These are then followed by proper integration of the components and software (if any) and tested on functional mock-ups and, finally, installation and test on an air vehicle. For safety reasons it is not feasible to demonstrate fault tolerance of primary control components during flight. These types of tests should be accomplished at the subsystem level and demonstrated in a mock-up and simulator. Other system level tests, such as electrical and electromagnetic environmental effects testing, are typically required regardless of control type (except for purely mechanical and hydromechanical systems) but become more critical when electrical and/or electronic controls gain greater authority. Many air vehicle control systems use some form of electrohydraulic actuators. As previously implied, system-level testing is an incremental buildup process; one objective of which is to validate design requirements. Flight test evaluation and qualification of the flight control system is typically a handling qualities, aeroelastic qualities, human factors, performance, reliability, and vulnerability evaluation. Qualification testing typically ends with user tests that include an evaluation of logistic characteristics. Mission capabilities are typically evaluated. The AQS should define the requirements for qualification. For the purposes of this handbook, there are six types of systems: fly-by-wire/fly-by-light systems, stability augmentation systems (SAS), autopilots, engine controls, instrument landing systems, and unmanned aerial vehicle (UAV) systems. With the exception of UAV systems, all systems perform the functions of providing pilot assistance through automatic or semiautomatic flight path control, or they automatically control airframe responses to disturbances. These functions are included in the definition of automatic flight control systems (AFCS) used in MIL-F-9490, *Flight Control Systems—Design, Installation, and Test of Piloted Aircraft, General Specification for,* (Ref. 44). MIL-F-9490 should be used as a guide to performing portions of the AQS and test plans for the AFCS. Specific requirements should be specified in the contract.

MIL-F-9490 contains AFCS operational state definitions, allowable degradations for AFCS component failures, and other testing information. These degradation levels should be used to determine the fail-safe and fail-degraded test requirements for the AFCS. Fail-safe systems testing should specify the minimum operational state allowable, e.g., State III minimum safe operation, whereas fail-degraded testing may allow a defined number of state degradations, e.g., no more than two states lower after failure.

Testing of those systems should be complementary to design and analysis activities. When the PA determines that AC analyses of AFCS is sufficient to ensure compliance with specifications, testing should not be required. Information concerning analysis requirements is included in par. 4.2 of MIL-F-9490 (Ref. 44).

Vulnerability performance requirements should be specified in the air vehicle specification. Validation requirements should be specified in the AQS. Primary testing should involve function, degree of pilot assistance, and vulnerabilities to natural environments, adverse events of nature, induced environments, onboard failure of other systems, maintenance error, flight crew error, and enemy actions. Information concerning these topics can be found in MIL-F-9490 as are the requirements for test witnessing, acceptance testing, instrumentation, and test conditions.

9-15.1 FLY-BY-WIRE/FLY-BY-LIGHT SYSTEMS

As previously stated, whether control forces are transmitted by mechanical linkage or by electrical wires and fiber-optic cable does not greatly influence the task of flight control qualification. Fly-by-wire and fly-by-light flight control systems include subsystems in which linkage between the pilot's controls and the control surfaces or controlled mechanism is implemented with electrical signals carried by wire or light energy in fiber-optic cables.

Each of these systems should successfully complete required AQS testing. Environmental test and evaluation should be a significant part of qualification. For information concerning test and evaluation, see MIL-STD-461, *Requirements for the Control of Electromagnetic Emissions and Susceptibility,* (Ref. 45) and MIL-STD-810, *Environmental Test Methods and Engineering Guidelines,* (Ref. 46). Fiber-optic systems tend to be susceptible to higher temperatures, especially at high altitudes. Although fiber-optic cables are not susceptible to an electromagnetic field, transistorized terminals might be susceptible. Wires are less susceptible to temperature yet more susceptible to electromagnetic fields. EMI and EMV testing is essential. Typically, system leveling testing should include but not be limited to

1. System safety-of-flight testing (software and hardware)
2. Air vehicle ground tests
3. Air vehicle flight tests.

Flight testing should not commence until a Contractor Flight Release for the current configuration (including the software used) has been issued. An Airworthiness Release will be needed if a Government pilot is in command of the air vehicle. Typical measurements during testing may include but not be limited to

1. Transient power effects
2. Interchangeability
3. Time to override computer inputs
4. Computation time as a percent of that available
5. Memory used and protection features
6. Software scaling constants.

Details of these measurements including the instrumentation requirements for these measurements are contained in MIL-F-9490.

Engine controls are covered separately in subpar. 9-15.4.

9-15.2 STABILITY AUGMENTATION SYSTEMS

Stability augmentation functions include traditional stability augmentation systems (SAS) as well as command augmentation systems and attitude hold, heading hold, position hold, velocity hold, and altitude hold systems. For rotorcraft ADS-33 (Ref. 22) defines the typical requirements for these systems as well as the requirements for operation after failure of these systems. For aircraft 14 CFR, Parts 23 and 25, (Refs. 4 and 5) are the appropriate documents. Verification of these requirements should form a part of flight loads, dynamic stability, and flying qualities demonstrations. Analysis of failure rates for SAS failures should be used to identify which failures are likely to occur during flight. Among the results of the analyses should be an identification of the specific axes affected, indication(s) to the aircrew, and aircraft response after failure. A system safety risk assessment is typically required by the PA.

The AC should also demonstrate provisions for SAS override and/or disengagement and selective reengagement of single axis SAS by the aircrew. Maximum airspeeds for SAS-off flight, engagement procedures, and operating restrictions or limitations for the air vehicle typically are established by the AC.

9-15.3 AUTOPILOTS

Autopilot subsystems perform the functions of providing pilot assistance through automatic or semiautomatic flight path control. This assistance may be intended to perform single functions such as altitude (barometric or absolute), heading, or airspeed hold or might be as extensive as to allow full mission flight from takeoff through enroute portions to touchdown. Automatic navigation functions are generally provided by systems called flight directors. These systems provide outer loop control of air vehicle direction and altitude through use of navigation sensors. Requirements regarding performance and qualification of these systems are derived from the DoD Flight Information Publications (FLIP) and FAA regulations, as appropriate. Qualification of these systems is most efficiently undertaken during navigation demonstrations because flying qualities are not typically of issue. MIL-F-9490 (Ref. 44) provides additional guidance regarding the performance requirements of these systems.

Since these subsystems are critical to safety of flight, the AC should use extensive analyses and simulation to prove the concepts and flight control algorithms prior to initiating flight test. Flight testing should be according to a test plan approved by the PA and should follow the guidelines of either a CFR or AWR issued by the PA. Minimum obstacle clearance altitudes are specified in the CFR or AWR as are flight restrictions, such as acceptable weather conditions (both ceiling and visibility) for testing.

Typically, development of the autopilot flight control algorithms necessitates development flight test. In these instances proposed obstacle clearance altitudes should begin at a minimum safe altitude and should be progressively reduced throughout the development test to allow safe conduct of the tests.

Following development testing, qualification testing conditions, altitudes, normal and emergency procedures, and autopilot performance capabilities should be demonstrated in accordance with a test plan. Typically, the AC should demonstrate multimode flight path guidance and crew override capabilities. Unless otherwise specified, automatic heading, altitude hold, attitude hold, velocity hold, and airspeed control should be demonstrated. Both qualitative and quantitative performance limits should be included. Reporting of qualification test results should be in sufficient detail to allow these characteristics and procedures to be included in operator's manuals.

9-15.4 ENGINE CONTROLS

Engine controls may involve mechanical linkages, electronic or fiber-optic components, and may be integrated with fire and flight control hardware and software. Electronic digital control systems allow more flexibility in providing load anticipation for a wide variety of situations. However, they are more difficult to evaluate and document due to the increased variables that affect engine and rotor governing. Critical characteristics of analog-to-digital and optical-to-digital conversions include frequency response, control loop time delays, and E^3 effects. The differences between qualification of electronic controls vs manual controls resides primarily at the component and subsystem levels. ADS-33 (Ref. 22) addresses aircraft performance characteristics during specific failures.

Par. 9-3 covers transient torque response and power turbine speed damping and frequency analyses. Typically, the AC demonstrates engine transient response, control transient response to engine failure, manual mode operation (if applicable), load sharing (if applicable), collective pitch lever pumps, rotor speed governing (dual and single), and torque-limiting capabilities. These demonstrations are accomplished on a power system mock-up or tied down air vehicle. Par. 9-6 discusses aerodynamic demonstration flight-performance-substantiating testing that can be considered other measures of functional performance. Portions of pars. 10-2 and 10-4 concern the reliability and maintainability characteristics of air vehicle subsystems, which provide information on probable operator and maintainer errors and failure mode, effects, and criticality analyses (FMECAs).
Pars. 9-7, 9-9, 9-10, and 9-11 discuss vibration testing, climatic laboratory testing, icing flight, electromagnetic vulnerability, lightning protection, and failure effects caused by other onboard failures related to vulnerabilities to induced and external environments. Par. 9-14 focuses on the survivability requirements for air vehicle subsystems. Successful accomplishment of this testing should at least partially satisfy the requirements for demonstration of function and degree of pilot assistance. Consequently, the AC should make every feasible effort to integrate engine control testing into other testing requirements to preclude duplication of effort.

9-15.5 INSTRUMENT LANDING SYSTEMS

The AC should demonstrate the capability of instrument landing systems to aid the pilot’s execution within specified limits of both precision and nonprecision approaches. Critical performance characteristics of the instrument landing system include altitude and position accuracy and failure or degradation detection. Instrument landing systems may include avionic and electronic systems designed to aid the aircrew’s performance of precision and both tactical and nontactical nonprecision approaches. An instrument landing system is basically a navigation subsystem that could have a flight control loop; hence objectives and measurements for a navigation subsystem apply in general. See par. 8-9. Also the flight control loop (if any) should be tested and qualified as discussed in this paragraph. Precision approach demonstration should involve glide path as well as ground track error measurements. If required by the PA, these error measurements should be correlated to cockpit indications and actual positions over the ground to determine the accuracy of the instrument landing system.

When coupled flight controls are incorporated, the AC plan to qualify the instrument landing system should include test procedures, limitations, minimum ceilings and visibilities, airspeeds, and recommended emergency procedures.

Part of the demonstration should involve degradation characteristics of the instrument landing system. A typical demonstration may be the indications to the pilot of loss of glide slope information, loss of power to instrument landing system components, and redundancy characteristics of the system.

If hybrid, integrated navigation systems, such as integrated global positioning system (GPS), inertial navigation system (INS), and Doppler navigation system, are identified for use in tactical approaches, the hierarchy of these systems should be identified, failure modes identified, and limitations established for degraded modes of operation.

9-15.6 UNMANNED AIR VEHICLE (UAV) SYSTEMS

There are two categories of unmanned air vehicles. Drone aircraft capable of manned flight is one category. Drone aircraft are used for a variety of purposes. In some cases they are used as targets. If capable of manned flight, all standard airworthiness objectives and measurements should apply. Also objectives and measurements of an unmanned air vehicle should apply. Another category is air vehicles that are not capable of manned flight. If the air vehicle is incapable of manned flight, only the objectives and measurements of the UAV will apply. Further, the objectives contained in DA PAM 73-1 (Ref. 38) might apply to either type of UAV. UAV flight control subsystems are controlled by remote operators or preprogrammed flight paths and algorithms. Hence an airworthiness release typically is not required; however, the need for some other type of release might be specified in the contract. Also the contract should specify who is responsible for ground and flight risks. A system safety risk assessment is typically required. Since no onboard human intervention is possible, the AC should demonstrate the ranges and effectiveness of the control data link, system reliability, navigation accuracy, and resistance to jamming, etc. The AC should also demonstrate by analysis, simulation, and fight test the response in the event of a loss of control response. Typical measurements are control response, position accuracies, fuel consumption, signal strength, etc. If control response is lost, typical actions would include either a power-on or power-off dive, a climb and return to takeoff point, or a spiraling climb. These actions are shown in Fig. 9-9.

If a malfunctioning control system is the cause of loss of control response, successful return to home base is unlikely, and a dive response may be the only feasible alternative. If the UAV is expendable, severely damaged, or unable to return to home base, a spiraling climb to clear airspace over the mission area and flight away from the mission area may be the chosen course of action. If maximum range is exceeded, a climb and return home might bring the UAV back into range where control can be regained.

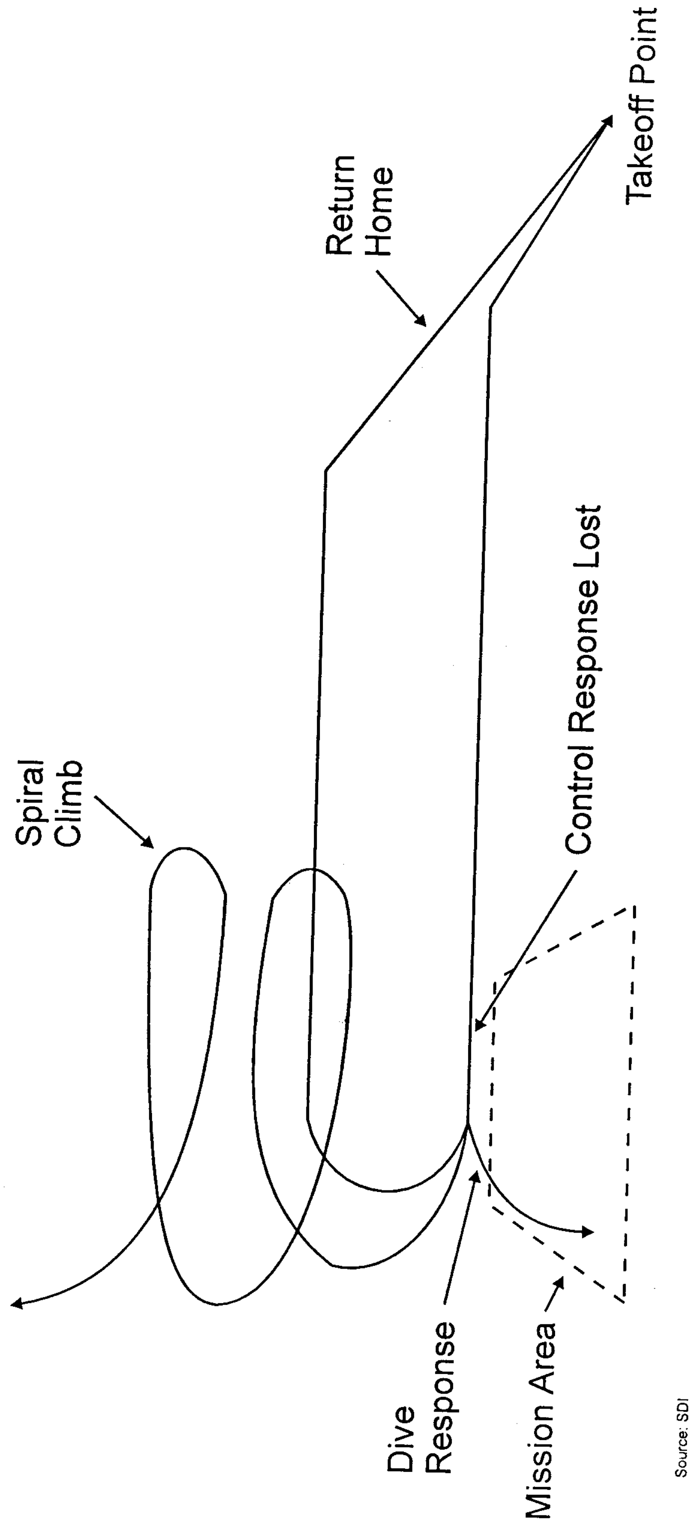


Figure 9-9 Unmanned Loss of Control Response

The AC should propose the procedures, algorithms, flight termination actions, and success criteria for UAV actions in the event of loss of control response. If required by the PA, flight test to demonstrate selected malfunctions may be required. Again since no onboard human intervention is possible, safety of ground personnel should be the primary concern during this testing, yet air traffic control is also an important issue. Demonstration of diagnostic and prognostic data links and flight termination hardware and software should ensure that

1. A flight termination condition is quickly and accurately identified
2. Initiation of the flight termination sequence has a very high probability of success, and the probability of flight termination is specified by the PA.

A typical measure of effectiveness may include the probability of failure detection, false alarms rates, probability of flight termination within a specified time period, etc.

9-16 TEST-ANALYZE-FIX-TEST (TAFT)

During the testing covered in this chapter, problems and malfunctions will undoubtedly occur. Once these events have occurred, failure analysis should be implemented to identify the root cause of the problems and any dependent malfunctions. Failure analysis should be used to identify fixes. The analysis is successful if it identifies the root cause of the malfunction. The AC should propose a fix in accordance with the terms of the contract. In the event that significant testing effected by the fix has already occurred, affected data points should be repeated. Also the PA should identify tests that should be repeated from the point of failure or from the beginning. An example of such tests may be a propulsion system endurance test that was not successfully completed due to a failure. Once the failure analysis is completed and the fix is implemented, the PA may require that the test be rerun completely. Other testing may allow continuation of the test from the point of failure with limited regression testing.

9-17 SAFETY

No hazardous or radioactive materials should be incorporated into an air vehicle unless the operational benefit outweighs the associated risks. Any such materials present well-defined potential hazards that should be thoroughly assessed and minimized. Also laser radiation hazards should be addressed. Information concerning laser radiation hazards can be found in MIL-STD-1425, *Safety Design Requirements for Military Laser and Associated Equipment*, (Ref. 47). Testing should be performed to ensure the hazards are well-defined and minimized.

REFERENCES

1. MIL-W-6729, *Watertightness of Aircraft, General Specification for*, 8 March 1993.
2. MIL-S-8698, *Structural Design Requirements, Helicopters*, 28 February 1958.
3. ADS-29, *Structural Design Criteria for Rotary Wing Aircraft*, US Army Aviation Systems Command, St. Louis, MO, September 1986.
4. 14 CFR, Part 23, *Airworthiness Standards: Normal Utility, Acrobatic, and Commuter Category Airplanes*, US Government Printing Office, Washington, DC, 1 January 1994.
5. 14 CFR, Part 25, *Airworthiness Standards: Transport Category Airplanes*, US Government Printing Office, Washington, DC, 1 January 1994.
6. ADS-9C, *Propulsion System Technical Data*, US Army Aviation Systems Command, St. Louis, MO, April 1990.
7. ADS-27, *Requirements for Rotorcraft Vibration Specifications, Modeling and Testing*, US Army Aviation Systems Command, St. Louis, MO, June 1993.
8. 14 CFR, Part 33, *Airworthiness Standards: Aircraft Engines*, US Government Printing Office, Washington, DC, 1 January 1994.
9. 14 CFR, Part 35, *Airworthiness Standards: Propellers*, US Government Printing Office, Washington, DC, 1 January 1994.
10. 14 CFR, Part 29, *Airworthiness Standards: Transport Category Rotorcraft*, US Government Printing Office, Washington, DC, 1 January 1994.
11. 14 CFR, Part 121, *Certification and Operations: Domestic, Flag, and Supplemental Air Carriers and Commercial Operators of Large Aircraft,* US Government Printing Office, Washington, DC, 1 January 1994.
12. 14 CFR, Part 127, *Certification and Operations of Scheduled Air Carriers With Helicopters*, US Government Printing Office, Washington, DC, 1 January 1994.
13. 14 CFR, Part 135, *Air Taxi Operators and Commercial Operators,* US Government Printing Office, Washington, DC, 1 January 1994.
14. MIL-F-7872C, *Fire and Overheat Warning Systems Continuous, Aircraft: Test and Installation of,* 30 September 1987.
15. MIL-F-23447, *Fire Warning Systems, Aircraft, Radiation-Sensing-Type, Test and Installation of,* 16 September 1962.
16. MIL-E-52031D, *Extinguishers, Fire, Vaporizing-Liquid CF3BR, 2 3/4 Pound, With Bracket*, 5 September 1979.
17. MIL-E-22285, *Extinguishing System, Fire, Aircraft, High-Rate-Discharge-Type, Installation and Test of,* 27 April 1960.
18. AMCP 706-201, *Engineering Design Handbook, Helicopter Engineering, Part One, Preliminary Design*, August 1974.
19. AMCP 706-204, *Engineering Design Handbook, Helicopter Performance Testing*, August 1974.
20. *Flight Test Engineering Handbook*, Air Force Technical Report 6273, US Air Force Flight Test Center, US Air Force Systems Command, Edwards Air Force Base, CA, May 1951.
21. MIL-F-8785C, *Flying Qualities of Piloted Airplanes*, 24 September 1991.
22. ADS-33C, *Handling Qualities Requirements for Military Rotorcraft,* US Army Aviation Systems Command, St. Louis, MO, August 1989.
23. MIL-F-83300, *Flying Qualities of Piloted V/STOL Aircraft*, 31 December 1970.

24. AGARD *Flight Test Manual, Vol. 1, Performance,* NATO Advisory Group for Aeronautical Research and Development (AGARD), Neuilly-sur-Seine, France, 1995.
25. MIL-STD-1474C, *Noise Limits for Military Materiel*, 30 July 1993.
26. MIL-STD-1789A, *Sound Pressure Levels in Aircraft*, 19 July 1989.
27. ANSI S1.11-86, *Octave Band and Fractional, Octave Band Analog and Digital Filters, Specification for*, American National Standards Institute, New York, NY, 1986.
28. DoD Directive 3200.11, *Major Range and Test Facility Base,* 29 September 1980.
29. Advisory Circular 29-2, *Certification of Transport Category Rotorcraft*, Federal Aviation Administration, Washington, DC, 28 May 1983.
30. ADS-37A-PRF, *Electromagnetic Environmental Effects (E3) Performance and Verification Requirements,* US Army Aviation and Troop Command, St. Louis, MO, 28 May 1996.
31. MIL-STD-1795A, *Lightning Protection of Aerospace Vehicles and Hardware*, 20 June 1989.
32. MIL-STD-1757, *Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware*, 31 January 1993.
33. MIL-STD-1385B, *Preclusion of Ordnance Hazards in Electromagnetic Fields, General Requirements for,* 1 August 1986.
34. IEEE C95.1-1991, *IEEE Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*, The Institute of Electrical and Electronics Engineers, Inc., New York, NY, 27 April 1992.
35. DoDI 6055.11, *Protection of DoD Personnel from Exposure to Radio Frequency Radiation and Military Exempt Lasers*, 21 February 1995.
36. AR 385-63, *Policies and Procedures for Firing Ammunition for Training, Target Practice, and Combat,* 15 October 1983.
37. ADS-20A, *Armament/Fire Control System Survey*, US Army Aviation Systems Command, St. Louis, MO, 30 August 1989.
38. DA PAM 71-3, *Operational Testing and Evaluation Methdology and Procedures Guide*, 15 October 1979.
39. DoD Regulation 5000.2-R, *Mandatory Procedures for Major Defense Acquisition Programs (MDAPs) and Major Automated Information System (MAIS) Programs*, 15 March 1996.
40. ADS-11B, *Survivability Program, Rotary Wing*, US Army Aviation Systems Command, St. Louis, MO, May 1987.
41. MIL-STD-2089, *Aircraft Nonnuclear Survivability Terms*, 21 July 1981.
42. MIL-STD-2069, *Requirements for Aircraft Nonnuclear Survivability Program*, 24 August 1981.
43. MIL-T-27422B, *Tank, Fuel, Crash Resistant, Aircraft*, 13 April 1971.
44. MIL-F-9490D, *Flight Control Systems—Design, Installation, and Test of Piloted Aircrat, General Specification for*, 5 October 1992.
45. MIL-STD-461D, *Requirements for the Control of Electromagnetic Emissions and Susceptibility*, 11 January 1993.
46. MIL-STD-810E, *Environmental Test Methods and Engineering Guidelines*, 1 September 1993.
47. MIL-STD-1425A, *Safety Design Requirements for Military Lasers and Associated Support Equipment*, 30 August 1991.

ABBREVIATIONS AND ACRONYMS

AC	=	air vehicle contractor
AFCS	=	automatic flight control system
AGARD	=	advisory group for aeronautical research and development
AGL	=	above ground level
AIM	=	airborne intercept missiles
ANSI	=	aerican national standards institute
APU	=	auxiliary power unit
AQP	=	airworthiness qualification specification
AQSR	=	airworthiness qualification substantiation report
ASE	=	aircraft survivability equipment
AWR	=	airworthiness release
BDAR	=	battle damage assessment and repair
BVR	=	beyond visual range
CAS	=	command augmentation system
CDRL	=	contract data requirements list
CF_3BR	=	monubromotrifluromethane
CFR	=	contractor flight release
CG	=	center of gravity
CW	=	continuous wave
C	=	centigrade
F	=	fahrenheit
DOD	=	department of defense
DNW	=	doppler navigation systems
DRC	=	damage-risk criteria
dB	=	decibel
E^3	=	electromagnetic environmental effects
E^3RB	=	E3 requirements board
EED	=	electroexplosive device
EMC	=	electromagnetic compatibility
EMCAB	=	electromagnetic compatibility advisory board
EMCON	=	emission control
EME	=	electromagnetic environment
EMI	=	electromagnetic interference
EMV	=	electromagnetic vulnerability
ESD	=	electrostatic discharges
FAA	=	federal aviation administration
FLIP	=	flight information ;publications
FMECA	=	failure modes, effects, and criticality analyses
FOD	=	foreign object damage
GPS	=	global positioning system
GSE	=	ground support equipment
HCPE	=	hybrid collective protection equipment

HEL	=	high energy lasers
HEMP	=	high altitude electromagnetic pulse
HERF	=	hazards of electromagnetic radiation to fuel
HERO	=	hazards of electromagnetic radiation to ordnance
HERP	=	hazards of electromagnetic radiation to personnel
HISS	=	helicopter icing spray systems
HFC-125-CF_3HF_2	=	pentafluoroethane
HPM	=	high power microwave
HV	=	height velocity
IEEE	=	institute of electrical and electronic engineers
IGE	=	in ground effect
INS	=	inertial navigation system
IPE	=	individual protection equipment
IPS	=	inlet particle separator
IR	=	infrared
ISS	=	icing spray systems
J/S	=	jamming-to-system
LST	=	laser spot tracker
MFE	=	limit maneuvering envelope
MGT	=	measured gas temperature
MOE	=	measures of effectiveness
NATO	=	north atlantic treaty organization
NBC	=	nuclear, biological, and chemical contamination
NEMP	=	nuclear electromagnetic pulse
NOE	=	nap-of-the-earth
OBA	=	octave band analyzer
OBIGGS	=	on-board inert gas generating system
OEI	=	one-engine inoperative
OFE	=	operational flight envelope
OGE	=	out of ground effect
P-stat	=	precipitation static
R/C	=	radar cross section
RPM	=	revolutions per minute
RMS	=	root mean square
SAM	=	surface-to-air missiles
SAQ	=	statement of airworthiness qualification
SAS	=	stability augmentation system
SFE	=	service flight envelope
SHP	=	shaft horsepower
SLM	=	sound level meter
TADS	=	target acquisition and designation sight
TREE	=	transient radiation effects on electronics
UAV	=	unmanned aerial vehicle
USAARL	=	us army aeromedical research laboratory
USACHPPM	=	us army center for health promotion and preventive medicine

USAEHA	=	us army environment hygiene agency
V/STOL	=	vertical/short take-off and landing
VROC	=	vertical rate-of-climb
VTOL	=	vertical take-off and landing
V_D	=	design dive speed
W/SR	=	radiant intensities